

National Aeronautics and Space Administration



SCIENCE PLAN

2014



CONTENTS



CHAPTER 1

Our Journey of Discovery.....1

CHAPTER 2

The National Agenda for Science at NASA.....5

2.1 National Policy Direction on Earth and Space Sciences.....7

2.2 Recommendations from the U.S. Scientific Community.....9

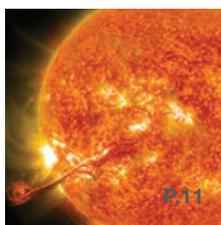
CHAPTER 3

A Plan for Science at the Frontiers.....11

3.1 Principles.....12

3.2 Strategies.....14

3.3 Challenges.....15



CHAPTER 4

Detailed Plans by Science Area.....25

4.1 Heliophysics.....26

4.2 Earth Science.....42

4.3 Planetary Science.....60

4.4 Astrophysics.....74



CHAPTER 5

A Plan for Joint Agency Missions.....89

CHAPTER 6

Advancing Technology for Science.....95

CHAPTER 7

Engaging the Next Generation.....101



APPENDICES

A. Status of NRC Decadal Survey Recommendations
and/or National Priorities.....108

B. NASA Strategic Goals and Objectives, SMD Division Science
Goals, Decadal Survey Priorities, and SMD Missions.....113

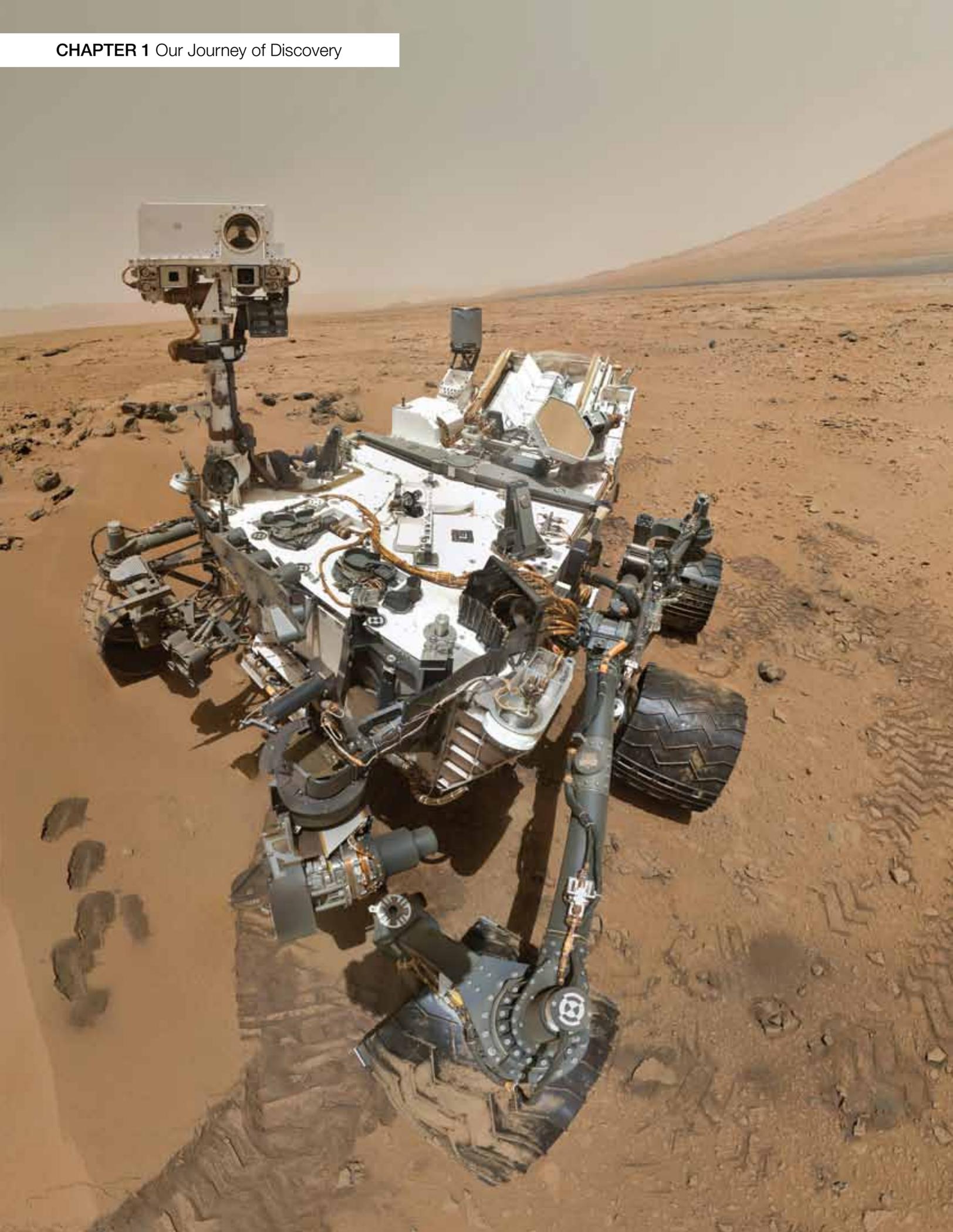
C. Program/Strategic Mission Lines.....115

D. Science Directorate Decision-Making Process for Missions.....116

E. References.....117

F. Acronyms and Abbreviations.....119





CHAPTER 1

Our **Journey** of Discovery

NASA leads the nation on a great journey of discovery, seeking new knowledge and understanding of our Sun, Earth, solar system, and the universe—out to its farthest reaches and back to its earliest moments of existence. The NASA Science Mission Directorate (SMD) and the nation’s science commu-

nity use space observatories to conduct scientific studies of the Earth and Sun from space, to visit and return data and samples from other bodies in the solar system, and to peer out into the vast reaches of the universe and beyond.

LEFT: On October 31, 2012, NASA’s Curiosity rover used the Mars Hand Lens Imager to capture this set of 55 high-resolution images, which were stitched together to create this full-color self-portrait. *Image Credit: NASA*



The NASA science program seeks to unravel the mysteries of our Sun, Earth, solar system, and the universe—out to its farthest reaches and back to its earliest moments of existence. *Image Credit: NASA/Jenny Mottar*

The knowledge gained by researchers supporting NASA's Earth and space science program helps to unravel mysteries that intrigue us all.

- What drives variations in the Sun, and how do these changes impact the solar system and drive space weather?
- How and why are Earth's climate and environment changing?
- How did our solar system originate and change over time?
- How did the universe begin and evolve, and what will be its destiny?
- How did life originate, and are we alone?

NASA SMD has developed science objectives and programs to answer these questions in the context of our national science agenda. Each of SMD's four science divisions—Heliophysics, Earth Science, Planetary Science, and Astrophysics—makes important contributions to address national and Agency goals.

Heliophysics is the study of the physical domain dominated by the Sun and its extension into space—the heliosphere.

This physical domain includes our Sun and the space environments of Earth and other planets, and stretches out to the region of interstellar space. Heliophysics is the oldest science discipline studied from space and even pre-dates NASA. In 1958, the first U.S. space satellite, Explorer 1, discovered the Van Allen radiation belts, a fundamental feature of planetary magnetospheres and a critical heliophysics phenomenon. The Sun's variability and extended atmosphere drive some of the greatest changes in our local magnetic environment, affecting our own atmosphere, ionosphere, and our climate. Heliophysics is also the underlying science of space weather. Space weather directly affects the safety of humans in space and on Earth by influencing the operation of electrical power grids, communications and navigation systems, gas and oil pipelines, and spacecraft electronics and orbital dynamics. At the dawn of the Space Age, heliophysicists were focused on these near-Earth assets. Now we view heliophysics as a much broader discipline. NASA has sent probes throughout the solar system and beyond into interstellar space. To protect these robotic assets and the humans who will inevitably follow them, we must learn to predict space weather reliably anywhere, any time, throughout the solar system.

From space, researchers view Earth as a planet and study it as a complex, interacting dynamic system with diverse components: the oceans, atmosphere, continents, ice sheets, and life itself. We observe and track changes on a global scale, connecting causes to effects, and we study regional changes in their global context. We observe the role that human civilization increasingly plays as a force of change. Through our partnerships with other agencies that maintain forecast and decision support systems, such as the National Oceanic and Atmospheric Administration (NOAA), United States Geological Survey (USGS), and Environmental Protection Agency (EPA), NASA improves national capabilities to predict climate, weather, and natural hazards; to manage resources; and to develop environmental policy. NASA's Earth science activities are an essential part of national and international efforts to understand global change and use Earth observations and scientific understanding in service to society.

NASA's planetary science program extends humankind's virtual presence throughout the solar system via robotic space probes to Earth's Moon, to other planets and their

moons, to asteroids and comets, and to icy bodies of the outer solar system. We are continuing humankind's reconnaissance of the solar system by sending missions to fly by Pluto, and to bring back a sample from a near-Earth asteroid. We are also in the midst of a systematic investigation of Mars, launching a series of progressively more capable orbiters, landers, and rovers, with the long-term goal of supporting future sample return and human exploration. Mars is rich with historical evidence of liquid water, helping us answer questions about habitability on alien worlds and the evolution of life in our solar system. We are also focusing research on the moons of Jupiter and Saturn, where we see intriguing signs of surface activity and of liquid water within, knowing that on Earth, where there is water and an energy source, there is also life.

NASA's astrophysics research enables us to learn wondrous things about our physical universe—the Big Bang and black holes, dark matter and dark energy, and the interrelated nature of space and time. Theories explaining these phenomena challenge NASA scientists to develop new methods of observations that can test these theories and our understanding of fundamental physics. We have measured the age of the universe, and now seek to explore its ultimate extremes—its birth, the edges of space and time near black holes, and the mysterious dark energy filling the entire universe. Our space missions are using nearly the full electromagnetic spectrum to observe the cosmos to understand the diversity of planets and planetary systems in our galaxy. In 2014, we will be approaching confirmation of the existence of almost 2000 planets that orbit stars other than our Sun, and will have discovered thousands of candidate planets around other stars. Some of these extrasolar planets are small, rocky bodies where liquid water could exist, and the next step is to confirm their habitability and eventually look for the signs of life.

NASA's journey of scientific discovery also helps motivate, support, and prepare for human expansion into the solar system. Science missions characterize the radiation environment of deep space, the pressure and composition of diverse planetary atmospheres, the terrain and geology of planetary surfaces, and the nature and origin of small bodies. They identify the hazards and resources present as humans explore space, and the science questions and

regions of interest that warrant detailed examination by human explorers.

NASA's science vision is to use the vantage point of space to achieve with the science community and our partners a deep scientific understanding of the Sun and its effects on the solar system, our home planet, other planets and solar system bodies, the interplanetary environment, and the universe beyond. In so doing, we lay the intellectual foundation for the robotic and human expeditions of the future, while meeting today's needs for scientific information to address national concerns such as climate change and space weather. At every step, we share the journey of scientific exploration with the public, and partner with others to substantially improve science, technology, engineering, and mathematics (STEM) education nationwide.

Scientific priorities for future NASA science missions are guided by decadal surveys produced by the National Research Council (NRC) of the National Academy of Sciences. The first Earth science decadal survey was published in early 2007. New decadal surveys in astrophysics, planetary science, and heliophysics were released in 2010–2012, as was the midterm assessment of the Earth science decadal survey. NASA uses these surveys as the principal source of science community input into its science planning processes.

NASA issues a strategic plan every four years. To complement the NASA strategic plan, NASA SMD produces a science plan at the same cadence. This 2014 edition of the science plan focuses on changes to the program planned for 2014–2018. The next edition of the science plan is scheduled for early 2018, and will be informed by a new Earth science decadal survey and potentially the midterm assessments of the astrophysics, planetary science, and heliophysics decadal surveys.

This NASA *2014 Science Plan* reflects the direction NASA has received from our government's executive branch and Congress, advice received from the nation's scientific community, the principles and strategies guiding the conduct of our activities, and the challenges SMD faces. The science plan that results enables NASA, as stated by NASA Administrator Charles Bolden, to “do the *best* science, not just more science.”



CHAPTER 2

The **National Agenda** for Science at NASA

LEFT: A 'Blue Marble' image of the Earth taken from the Visible Infrared Imaging Radiometer Suite instrument aboard Suomi NPP (Suomi National Polar-Orbiting Partnership). *Image Credit: NASA*

NASA science contributes directly and substantially to current national priorities by:

Leading Fundamental Research: NASA is a leading scientific research organization working in and across the fields of heliophysics, Earth science, planetary science, and astrophysics. As of 2014, NASA's science program has close to 125 spacecraft in operation, formulation, or development, generating science data accessible to researchers everywhere. More than 10,000 U.S. scientists in academia, industry, and government laboratories funded by approximately 3,000 competitively selected NASA research awards are working to answer fundamental science questions of societal importance. NASA is unique among government agencies because it supports this broad and inclusive extramural research program with major research and development efforts at its ten centers to create the observational capability, new approaches, and research utilization capabilities that enable the scientific community to continue to make discoveries.

Enhancing Environmental Stewardship: Understanding the causes and consequences of climate change is one of the greatest challenges of the 21st century. NASA's advanced space missions within its Earth science research, applications, and technology program make essential contributions to national and international scientific assessments of climate change that governments, businesses, and citizens all over the world rely on in making many of their most significant investments and decisions. Through the U.S. Global Change Research Program (USGCRP), NASA works in partnership with thirteen other federal agencies to determine the relative impact of human-induced and naturally occurring climate change, addressing an important scientific challenge and providing significant societal benefit.

Inspiring the Next Generation and Creating a World-class Workforce of Scientists and Engineers: Stunning imagery and data visualizations from the Hubble Space Telescope (HST), the Solar Dynamics Observatory (SDO), and the Saturn orbiter Cassini; the exploits of the Mars rovers; and the amazing discoveries of other space and Earth science missions spark imagination, inspire students to pursue STEM education and career fields, and encourage people to become scientifically knowledgeable citizens who



NASA launched the Balloon Array for Radiation-belt Relativistic Electron Losses (BARREL) over Halley Research Station in February 2014 to float above Antarctica and observe magnetic fields to augment measurements from the Van Allen Probes spacecraft. *Image Credit: NASA*

will be better able to participate in science-related activities. The thousands of scientists funded by NASA are, in turn, training graduate students and postdoctoral fellows, teaching undergraduates, and providing research results for use in teacher-tested education tools. Engineers and scientists at NASA and its industrial and university partners are training their junior peers, teaching in formal and informal educational settings, and inventing new design tools for the workforce of the future. Our premier scientific laboratories, mission teams, and NASA-funded academic groups feed the broader U.S. technical workforce with employees that embody the values of excellence, innovation, and service.

Driving Technological Innovation: NASA science missions are engines of innovation, leveraging technologies to solve scientific problems. These technologies enable the advanced space missions of the future, and yield applications in the broader economy in various fields such as health care that rely on imaging, data mining, and visualization technologies. For example, technologies and techniques developed to accurately measure the shape of the mirrors for the James Webb Space Telescope (JWST) have enabled improvements in wavefront sensing technology that are now used by ophthalmologists to collect detailed information about aberrations in the shape of the human



Developed in conjunction with Homeland Security's Science and Technology Directorate, the prototype technology called Finding Individuals for Disaster and Emergency Response (FINDER) is based on remote sensing radar technology developed by the NASA Jet Propulsion Laboratory. FINDER can locate individuals buried as deep as 30 feet (9 meters) in crushed materials or hidden behind 20 feet (6 meters) of solid concrete. *Image Credit: NASA/Bill Ingalls*

eye in seconds, rather than hours. These improvements in measurement technology can improve the diagnosis of ocular diseases and potentially improve the precision of the measurements needed during surgeries.

Extending Partnerships Domestically and Internationally: Science is a broad national and international enterprise. SMD partners with over a dozen U.S. federal agencies and more than 60 different nations and international research organizations to leverage ideas, capabilities, and resources. NASA and the National Science Foundation (NSF) collaborate to advance our understanding of the universe, with NASA providing the space-based observatories, and NSF the ground-based observatories. NASA and the Department of Energy (DOE) partner on selected space missions to study the fundamental physical laws of the universe, and to develop nuclear power sources for robotic space missions. NASA partners with established and emerging spacefaring nations to send spacecraft to asteroids, comets, and other planets. Using spacecraft observations, NASA develops models of space weather and collaborates through the National Space Weather Program with agencies such as NOAA and the Department of Defense (DOD), who use the models in operational forecasting systems.

SMD's Joint Agency Satellite Division (JASD) manages the development and launch of weather satellites for NOAA on a reimbursable basis and works with NOAA as it adopts data and measurement technologies for operational observing systems. The United States Department of Agriculture (USDA), Federal Aviation Administration (FAA), EPA, USGS, and many other agencies are users of NASA's Earth science data. SMD collaborates with the NSF on research about Antarctica that spans all four SMD science disciplines. Like the International Space Station (ISS), NASA's Sun, Earth, solar system, and distant universe observatories are models of international and interagency cooperation and serve to further common scientific interests.

As a federal agency, NASA implements policy direction from the government's executive and legislative branches. As a science organization, NASA seeks advice from the broad national science community to identify the most important scientific questions and to define and prioritize the scientific research programs that most effectively address those questions. Based on this direction and advice, NASA defines its science plan.

2.1 National Policy Direction on Earth and Space Science

The Space Act, and the 2008 and 2010 Congressional Authorizations

The *National Aeronautics and Space Act of 1958* (P.L. 85-568, July 29, 1958) established NASA's mandate to conduct activities in space to accomplish national objectives, including "the expansion of human knowledge of the Earth and of phenomena in the atmosphere and space" and "the development and operation of vehicles capable of carrying instruments, equipment, supplies, and living organisms through space." The act specifies functions to be performed by NASA including the following:

- Arrange for participation by the scientific community in planning scientific measurements and observations to be made through use of aeronautical and space vehicles, and conduct or arrange for the conduct of such measurements and observations.

CHAPTER 2 The National Agenda for Science at NASA

- Provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof.

In the *NASA Authorization Act of 2008* (P.L. 110-422, Oct. 15, 2008), Congress states several findings regarding the science programs at NASA:

- NASA is and should remain a multi-mission agency with a balanced and robust set of core missions in science, aeronautics, and human space flight and exploration.
- NASA should assume a leadership role in a cooperative international Earth observations and research effort to address key research issues associated with climate change and its impacts on the Earth system.
- Human and robotic exploration of the solar system will be a significant long-term undertaking of humanity in the 21st century and beyond, and it is in the national interest that the United States should assume a leadership role in a cooperative international exploration initiative.

In the *NASA Authorization Act of 2008* Congress also mandates some specific programmatic activities for NASA:

- Monitoring and assessing the health of Earth's stratosphere
- Participating in an interagency program to provide land remote sensing data
- Tracking and characterizing near-Earth objects greater than 140 meters in diameter

The *NASA Authorization Act of 2010* (P.L. 111-267, Oct. 11, 2010) states that NASA should remain a multi-mission agency with a balanced and robust set of core missions. The act also lists several Congressional findings including the following:

- It is critical to identify an appropriate combination of NASA and related United States Government programs, while providing a framework that allows partnering, leveraging and stimulation of the existing and emerging commercial and international efforts in both near Earth space and the regions beyond.
- It is essential to the economic well-being of the United States that the aerospace industrial capacity, highly

skilled workforce, and embedded expertise remain engaged in demanding, challenging, and exciting efforts that ensure United States leadership in space exploration and related activities.

U.S. National Space Policy

The President issued the *National Space Policy of the United States of America* on June 28, 2010. The policy includes among NASA's responsibilities the following that pertain to SMD:

- Maintain a sustained robotic presence in the solar system to: conduct scientific investigations of other planetary bodies; demonstrate new technologies; and scout locations for future human missions.
- Continue a strong program of space science for observations, research, and analysis of our Sun, solar system, and universe to enhance knowledge of the cosmos, further our understanding of fundamental natural and physical sciences, understand the conditions that may support the development of life, and search for planetary bodies and Earth-like planets in orbit around other stars.
- Pursue capabilities, in cooperation with other departments, agencies, and commercial partners, to detect, track, catalog, and characterize near-Earth objects to reduce the risk of harm to humans from an unexpected impact on our planet and to identify potentially resource-rich planetary objects.
- Conduct a program to enhance U.S. global climate change research and sustained monitoring capabilities, advance research into and scientific knowledge of the Earth by accelerating the development of new Earth observing satellites, and develop and test capabilities for use by other civil departments and agencies for operational purposes.
- Work with NOAA to support operational requirements for environmental Earth observations and weather, including transitioning of mature research and development satellites to long-term operations. NOAA will primarily utilize NASA as the acquisition agent for operational environmental satellites for these activities and programs.
- Work together with the USGS in maintaining a program for operational land remote sensing observations.

Responding to the Challenge of Climate and Environmental Change

Earth's changing environment impacts every aspect of life on our planet and climate change has profound implications on society. Understanding the causes and consequences of climate change is one of the greatest challenges of the 21st century. In response to the challenge, the government's executive branch increased its emphasis on climate research and monitoring. In 2010, NASA enhanced the Earth science program defined by the 2007 National Research Council decadal survey with the addition of climate-focused measurements, as described in the Agency's climate-centric architecture plan, *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space* (NASA, 2010). Efforts towards implementing this architecture within SMD are detailed in chapter 4.2.

2.2 Recommendations from the U.S. Scientific Community

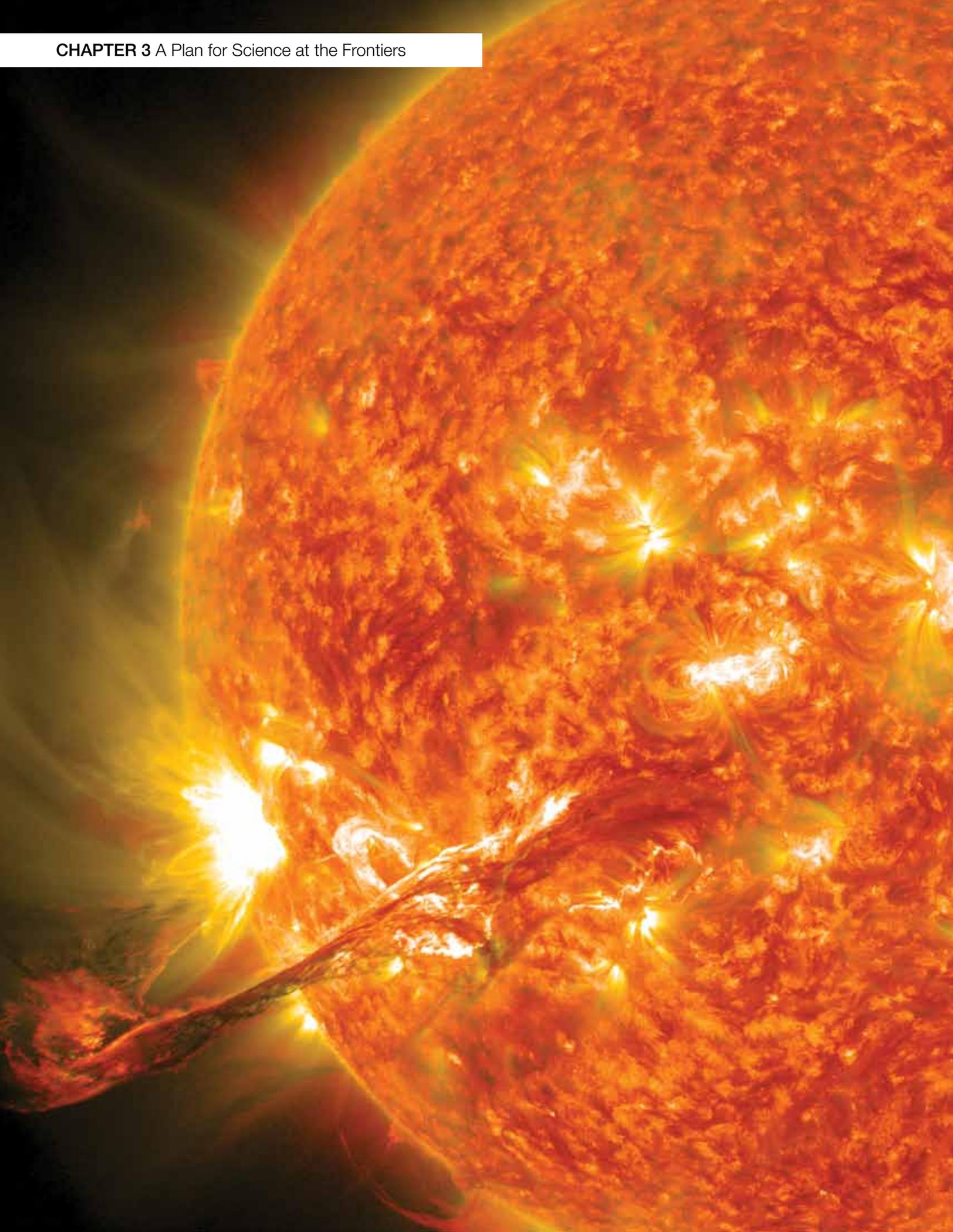
As NASA aligns its science programs with national policy, it also works towards implementing the priorities defined in the decadal surveys produced by the National Research Council (NRC) of the National Academies. The decadal surveys are the result of a science and mission prioritization process executed by expert panels using broad community input gathered by representative committees. The NRC analyzes the input with the goal of articulating community priorities within the scientific scope of each survey. As such, decadal surveys represent the broad consensus of the nation's scientific communities and are the starting point for NASA's strategic planning process in the arenas of Earth and space sciences.

The NRC produces decadal surveys for each of NASA's four major science disciplines:

- *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (NRC, 2007)
- *Vision and Voyages for Planetary Science in the Decade 2013–2022* (NRC, 2011)
- *New Worlds, New Horizons in Astronomy and Astrophysics* (NRC, 2010)
- *Solar and Space Physics: A Science for a Technological Society* (NRC, 2013)

Progress in implementing the science mission concepts recommended in current decadal surveys is described in Appendix A. In some areas, other reports by the NRC provide additional recommendations on matters arising since the publication of the last decadal survey. For example, NRC reports such as *Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce* (NRC, 2010), *Controlling Cost Growth of NASA Earth and Space Science Missions* (NRC, 2010), and *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions* (NRC, 2011) offer NASA additional insight and advice on how to effectively implement NASA's science program. As intervening accomplishments and new scientific challenges are presented, new NRC studies will provide additional recommendations that NASA will take into consideration.

NASA receives ongoing programmatic advice from the science community through the NASA Advisory Council (NAC) and its Science Committee and subcommittees. The NAC has suggested development of community-based roadmaps that define approaches to implementing the decadal survey science priorities, and factoring in technology readiness and synergies among science objectives and measurement types. Information on the science subcommittees, including their reports and findings, can be accessed at: <http://science1.nasa.gov/science-committee>. In addition, NASA receives advice from the Astronomy and Astrophysics Advisory Committee (AAAC) and Applied Sciences Advisory Group (ASAG), which were both chartered by Congress. AAAC conveys community input on collaborative program opportunities for NSF, NASA, and DOE, and ASAG provides community strategic and programmatic guidance for Earth science Applied Science Program activities.



CHAPTER 3

A Plan for Science at the Frontiers

LEFT: On August 31, 2012 a long filament coronal mass ejection (CME) erupted from the Sun traveling at over 900 miles per second. The CME did not travel directly toward Earth, but did connect with Earth's magnetic environment, or magnetosphere, causing aurora to appear. *Image Credit: NASA*

NASA's 2014 strategic plan outlines the following science goals for the Agency:

- Expand the frontiers of knowledge, capability, and opportunity in space
- Advance our understanding of our home planet and improve the quality of life

The Agency, through SMD, implements its science goals through four broad strategic objectives, each corresponding to a specific science discipline:

- Understand the Sun and its interactions with Earth and the solar system, including space weather (Heliophysics)
- Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet (Earth Science)
- Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere (Planetary Science)
- Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars (Astrophysics)

NASA SMD science divisions accomplish the Agency's science objectives. Building on the NRC decadal surveys and interaction with the NAC and its Science Committee and subcommittees, each SMD science division has defined a set of science questions and goals upon which to base its research and mission programs (see chapter 4). Appendix B lists these SMD-generated science goals and correlates them with the Agency's overall goals and science strategic objectives, the decadal survey priorities, and the SMD missions.

The principles, strategies, and challenges described in this chapter shape SMD's plans for progress in all of its science disciplines. The principles are enduring over long periods and guide SMD activities. The strategies are also long-range in nature but adapt to changing national goals, new scientific understanding and technologies, and evolving Agency policies. The challenges span all time frames and SMD must continuously look for every opportunity to overcome them.

3.1 Principles

SMD's strategic decisions for future missions and scientific pursuits are driven by priorities recommended in the NRC decadal surveys, adjusted to address national needs, and guided by a commitment to preserve a balanced program across the four major science disciplines. The fundamental success criteria for SMD are (1) progress in answering the SMD science questions, (2) implementation of the decadal survey priorities, and (3) responding to direction from the executive branch and Congress. SMD engages the Science Committee of the NAC and its subcommittees annually to rate scientific progress. In addition, Congress directed in the *NASA Authorization Act of 2005* (P.L. 109-155, Dec. 30, 2005) that the performance of each division in the NASA Science Mission Directorate shall be reviewed and assessed by the National Academy of Sciences at 5-year intervals. In compliance with this directive, the midterm assessment for Earth science was completed in 2012 with a favorable assessment, and the midterm assessments for astrophysics, planetary science and heliophysics will be released in 2015–2017. The NRC anticipates a new decadal survey for Earth science will also be released in 2017–2018. In addition to the decadal surveys, programs in the Earth Science Division (ESD) are also responsive to national priorities. In 2010, NASA responded to the challenge of climate change by issuing an Agency plan for a climate-centric architecture that would guide missions and scientific pursuits of SMD's Earth Science Division for FY11 and beyond.

Investment choices are based on scientific merit via peer review and open competition.

SMD uses open competition and scientific peer review as the primary means for establishing merit for selection of research and flight projects. SMD solicits individual scientist-led research investigations primarily via the annual Research Opportunities in Space and Earth Sciences (ROSES) omnibus NASA Research Announcement (NRA). Amendments to ROSES are issued, as needed, for new opportunities unanticipated at the time of the ROSES NRA release. For competed space missions, NASA solicits complete scientific investigations involving new space missions via Announcements of Opportunity (AO). For strategic missions, NASA solicits scientific instruments via AOs. Strategic missions are defined based on NRC decadal surveys and national policy direction. NASA

also occasionally issues Cooperative Agreement Notices for the establishment of virtual research institutes or for other purposes. Active virtual research institutes include the NASA Astrobiology Institute (NAI), and the NASA Solar System Exploration Research Virtual Institute (SSERVI).

Active participation by the research community beyond NASA is critical to success. SMD engages the external science community in the establishment of science priorities, preparation and review of plans to implement these priorities, analysis of requirements and trade studies, conduct of research, and evaluation of program performance. Strategic-level science advice on priorities is sought from the community primarily through NRC boards, committees, and studies. Tactical-level advice on implementing priorities is sought primarily from the scientific community via the Science Committee of the NAC and its subcommittees. SMD often engages the community through analysis groups that perform technical studies, such as mission architecture analyses, prior to conceptual design. Informal interaction with the science community occurs through meetings of the community's professional societies, such as the American Astronomical Society, the American Meteorological Society, and the American Geophysical Union.

Effective international and inter/intra-agency partnerships leverage NASA resources and extend the reach of our science results. International and interagency partnerships have long been a means to leverage SMD resources to accomplish shared science objectives. Over half of SMD's space missions involve co-investigating partners. These partnerships range from provision of science instruments, spacecraft buses, and launch vehicles, to data sharing arrangements. NASA holds regular bilateral meetings with major partners to discuss the full range of current and potential partnerships. For example, NASA and the European Space Agency (ESA) are actively engaged in dialogue about cooperation on future space missions, operations and data management, planetary protection, and calibration/validation activities in support of current and future satellite missions. NASA partners with other federal agencies, as well as with state and regional organizations, to enable satellite observations and research to improve the tools used by these organizations to advance scientific understanding and deliver essential services to the nation. These services include weather forecasting, wildfire management, coastal

zone management, agricultural crop yield forecasting, air quality assessment, near-Earth object (NEO) tracking, and space weather monitoring. Additionally, SMD partners within NASA to collectively meet complementary goals across mission directorates. For example, SMD partnered with the Human Exploration and Operations Mission Directorate (HEOMD) to measure the radiation environment from inside the spacecraft of the Mars Science Laboratory mission during its cruise to Mars—data that is mutually beneficial to both NASA directorates as they plan for future human and robotic deep space exploration. SMD has also partnered with the Space Technology Mission Directorate on coronagraph technology for future space telescopes. Additional major partnerships are identified in the science division-specific sections of chapter 4.

A balanced portfolio of space missions and mission-enabling programs sustains progress toward NASA's science goals. Sustained progress requires particular attention to a balanced science portfolio including basic research, modeling programs, technology development, missions, mission data analysis, and data and information systems. An NRC report, *An Enabling Foundation for NASA's Earth and Space Science Missions* (NRC, 2010), highlighted the importance of mission-enabling programs in meeting NASA's science goals. At NASA, space missions represent the largest area of investment. In accordance with NASA Procedural Requirement 7120.5e: *NASA Space Flight Program and Project Management Requirements* (NASA OCE, 2012), missions are grouped into distinct categories based on cost, the inclusion of radioactive material for human or robotic spaceflight, the importance of the mission to NASA, the extent of international participation, the uncertainty of new or untested technologies, and mission risk classification. Category 1 missions have a life cycle cost (LCC) that exceeds \$1 billion; offer high-value, broad, and long-range science return; and use the scientific, engineering, and project management expertise resident at NASA Centers and academic and industrial partners. They also provide substantial opportunities for international partnerships. Category 2 missions have an LCC of \$250 million to \$1 billion, and Category 3 missions have an LCC of less than \$250 million. Both Category 2 and 3 missions provide opportunities to broaden our research portfolio, to engage universities and other research institutions in mission development, and to ensure scientific vitality and

competition. Appendix C identifies the categories for each SMD program/strategic mission line. Suborbital programs, comprising sounding rockets, balloons, and aircraft, provide complementary observations, opportunities for innovative instrument demonstration, and a means for workforce development, as highlighted by the NRC in its report *Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce* (NRC, 2010).

Each SMD science division balances its portfolio based on myriad factors, including, for instance, that division's requirements in the President's budget request and priorities outlined in the decadal surveys. The goals and mission sets of the science divisions are unique and inevitably lead to distinct approaches toward achieving programmatic balance among missions, technology development, and research and analysis. Balance is discussed further in the science division-specific sections of chapter 4. Appendix D depicts the decision process NASA uses throughout the mission lifecycle to maintain a balanced and effective mission portfolio.

The pace of scientific progress is enhanced by rapid, open access to data from science missions. NASA requires that science data from its missions be made available as soon as practical after scientific validation. SMD invests substantially in active archive systems to enable public access to science data via the Internet and to preserve data that enables long-term records to be established and improved in climate change, comparative planetology, and other key areas.

The NASA mandate includes broad public communication. As a federal agency, NASA has a responsibility to communicate information about its programs and scientific discoveries to the public, and this responsibility is highlighted in NASA's founding legislation. As a research and development agency, NASA seeks to share its scientific discoveries with as broad an audience as possible. In accordance with the guidance and direction established by the National Science and Technology Council (NSTC) Committee on Science Technology, Engineering and Math Education (CoSTEM), and outlined in the *Federal Science, Technology, Engineering, And Mathematics (STEM) Education 5-Year Strategic Plan* (NSTC CoSTEM, 2013), NASA

implements targeted efforts to reach students in order to promote STEM education, improve science literacy, and inspire and train our future workforce.

Accountability, transparent processes, accessible results, and capture of lessons learned are essential features of this federal science enterprise. The nation makes a substantial investment in NASA's science program. Thus, it is incumbent upon SMD to provide a commensurate return on investment, to be accessible to its stakeholders, and to continue to improve based on lessons learned from both successes and failures. NASA reports on its progress through various means, including annual performance reports to Congress, regular meetings of its advisory committees, press releases, town hall meetings, publications in peer-reviewed journals, and frequent posting of developments on its website. SMD's website and the Service and Advice for Research and Analysis (SARA) website (an additional resource for proposal writing) provide portals into SMD's key business processes.

3.2 Strategies

Pursue answers to big science questions to which the view from space makes a defining contribution. NASA runs one of the nation's largest science programs, and accordingly, it seeks answers to some of the most profound questions in all of science, as described in chapter 1. A detailed set of science goals designed to answer those questions is given in Appendix B. Answering these questions requires observations and measurements made in and from space, including direct measurements made from the surface of planets and objects in our solar system, and ultimately the analysis of returned samples in Earth-based laboratories. SMD's investments in research and analysis and in technology are focused on: laying the foundation for these space-based missions, inventing and using new space-based observing and sampling capabilities, creating the context and capabilities needed to interpret the resulting data, and maximizing the return on investment in the acquisition of those data. SMD's suborbital and ground-based programs are conducted to enable or complement space-based observations and train future mission scientists and engineers. Sustained Earth observations using mature space-based assets are implemented in partnership with the agencies requiring those observations.

Design and successfully implement programs that accomplish breakthrough science and applications. In NASA, programs comprise a set of projects that together advance science in that program area. Significant tangible societal benefits flow from NASA research in heliophysics, Earth science, and other disciplines. Accomplishing breakthrough science with innovative space missions requires effective management of a program portfolio, and includes:

- Measuring mission success by accomplishment of top-level science requirements
- Establishing a budget for each new mission that matches a probable life-cycle cost defined by engineering studies and independent cost estimates
- Providing budget projections and mission concept cost ranges as basic input to NRC committees formulating decadal surveys
- Obtaining tactical-level community advice on portfolio adjustments via the NAC Science Committee and its subcommittees
- Implementing effective partnerships—international, inter-agency, academic and others—to help leverage NASA resources and extend scientific results, where applicable
- Using special peer review panels of senior scientists to determine the scientific value of continued operation of existing missions beyond their prime mission lifetimes

Partner with other nations’ space agencies to pursue common goals. Both longstanding and newly spacefaring nations have scientific interests similar to ours, which can be collaboratively pursued through basic research, suborbital campaigns, and competed or strategic missions. As missions become more ambitious and complex—progressing from fly-bys, to orbiters, to landers and rovers, to future sample return missions exploring other bodies in our solar system (e.g., the Moon, asteroids, and comets)—the cost of implementing them stresses the resources of any one nation. NASA has partnered with ESA and with the Japan Aerospace Exploration Agency (JAXA) successfully on numerous Earth and space science missions, and NASA continues to form additional partnerships with other countries. For strategic missions, international collaboration between agencies is based on an alignment of NASA’s and its partners’ science priorities, capabilities, and resources. For competed missions, international collaboration is

based on scientist-to-scientist collaboration in formulating proposed investigations.

Commit to implementing missions only after focused development has matured required technologies. Technology development programs are essential for expanding the reach of future scientific missions. In fact, progress in scientific understanding typically requires advancement in measurement or platform capabilities. A balanced science program will proactively identify potential technologies, conduct trade studies and assess development risks, and invest in new technologies well in advance of mission implementation. Investments in science-driven technologies then become available to proposers of new instruments and mission concepts throughout the science program.

Share the story, the science, and the adventure of NASA missions and research to engage the public in scientific exploration and contribute to improving science, technology, engineering, and mathematics (STEM) education nationwide. NASA’s science is unique among federal agencies. It inspires and engages students and people of all ages to learn about new science discoveries and to acquire new skills in science, technology, engineering, and mathematics. SMD is building strategic educational and public outreach partnerships to enhance the nation’s STEM education, as described in the *Federal STEM Education 5-Year Strategic Plan*.

3.3 Challenges

This section discusses the challenges that SMD faces in carrying out its science plan according to the principles and strategies outlined earlier. First the challenges that the Agency outlined in its *2010 Science Plan for NASA’s Science Mission Directorate* (NASA, 2010) are updated to reflect progress the SMD has made in addressing these challenges: access to space, mission cost estimation and management, technology development and demonstration, and impediments to international collaboration on space missions. Following these challenges are new issues for 2014–2018: protecting the planet while advancing science, national science and technology workforce development, long-term program planning, and unrealized expectations.

Access to Space

SMD relies on commercial expendable launch vehicles (ELVs) acquired for SMD by the Human Exploration and Operations Mission Directorate to launch its science missions into space. In the past few years, access to space has been hindered by the failure, discontinuation, or cost of launch vehicles.

For SMD small payload class missions, the small-class launch vehicles on contract to NASA are the Orbital Sciences Corporation (OSC) Pegasus XL and Taurus XL, and the Lockheed Martin Space Systems Company (LMSSC) Athena Ic. The Pegasus XL has had a successful launch history. The Taurus XL has higher lift performance capability than the Pegasus XL, but experienced two successive launch failures for SMD Earth science missions—the first in 2009 for the Orbiting Carbon Observatory (OCO) mission, and the second in 2011 for the Glory mission. The Athena Ic has not yet flown and remains ineligible to compete for the launch of an individual NASA payload.

For decades, the predominant medium class launch vehicle utilized by SMD has been the Delta II launch vehicle. As of 2014, one Delta II launch vehicle remains available for acquisition by NASA. Currently the medium-class launch vehicles on contract to NASA are the OSC Antares 120/130 series, the Space Exploration Technologies (SpaceX) Falcon 9, and the LMSSC Athena IIc. Certification activities for the Falcon 9 version 1.1 are underway to support the Jason 3 mission, which is scheduled for launch in March 2015. The Antares 120 successfully completed its first flight in January 2014, and is now eligible to compete for the launch of an individual NASA payload. Neither the Antares 130 nor Athena IIc has yet flown, and both remain ineligible to compete for the launch of a NASA payload.

For SMD large payload class missions, the Atlas V has had a successful launch history, albeit at a premium cost, principally due to the fact that it was the only certified launch vehicle on contract for large payload class missions. In addition, the Atlas V manifest is congested, due to competition for launch slots among the civil and military communities. In addition to medium class missions, the Falcon 9 version 1.1 is also capable of providing “Atlas V-like” performance for payloads going to low Earth orbit and is expected to

be comparable to the smallest Atlas V in performance for some planetary missions and geosynchronous transfer orbit missions. Once the Falcon 9 version 1.1 is certified, it is envisioned that competition between the intermediate-class launch vehicles should assist in lowering costs and may help reduce manifest congestion in the Atlas V fleet.

As an alternative to contracting for launch vehicles, NASA is exploring opportunities to fly instruments as hosted payloads on commercial satellites to reduce launch costs. This paradigm is similar to ridesharing or co-manifesting, but instead of sharing a launch vehicle, the instruments share a satellite bus.

Mission Cost Estimation and Management

SMD continues to develop and implement the cutting-edge technologies necessary to advance exciting scientific discoveries. However, more precise mirrors, advanced power systems, probes and satellites that can withstand hostile environments, and observatories that can be sustained for decades are inherently complex, so cost and schedule risks are inevitable. In an increasingly constrained fiscal environment, it is becoming even more important to execute SMD's missions on time and within budget. In the *2010 Science Plan for NASA's Science Mission Directorate*, SMD outlined the Agency's efforts to revise and implement new policies to constrain mission costs and meet schedule goals. These steps include:

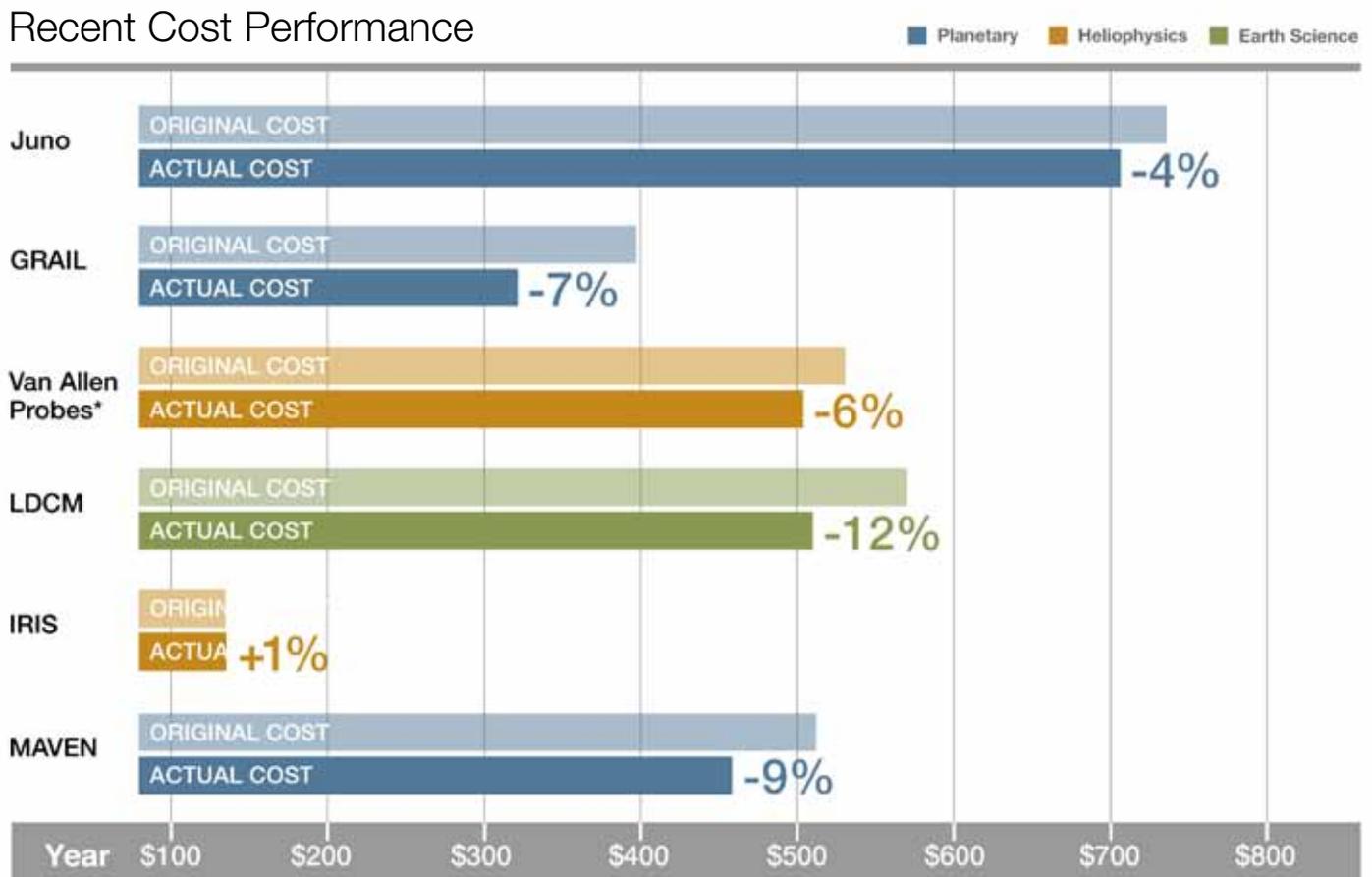
- Establishing mission life-cycle budgets at the 70% confidence level
- Obtaining multiple, independently generated internal and external cost estimates
- Reviewing projects at multiple, formal Key Decision Points that function as gates to the next stage of development
- As required by the *NASA Authorization Act of 2005*, preparing a report to Congress on any project expected to exceed 15 percent cost growth or delay its launch date milestone by more than six months from its baseline, identifying corrective actions, their costs, and any alternatives

Additionally, NASA requires that cost estimates of mission concepts submitted by NASA centers to NRC decadal survey committees be reviewed by an independent team of cost/schedule estimators and approved by the SMD Science Division Director. By following these steps over the last three years, NASA has launched several missions either under or within their cost and schedule baselines, demonstrating progress in improving the Agency’s mission cost estimation and management tools (see Figure 3.1).

This record of cost and schedule performance for SMD is historically unprecedented. The Van Allen Probes (formerly known as the Radiation Belt Storm Probes [RBSP]), Juno, Gravity Recovery and Interior Laboratory (GRAIL), Mars Atmosphere and Volatile Evolution (MAVEN) mission, and Landsat Data Continuity Mission (LDCM)/Landsat 8 did not require a re-baseline at any point during implementa-

tion, and were below the budget level originally promised. For some of the missions that exceeded original forecasts (e.g., Interface Region Imaging Spectrograph [IRIS]) cost overruns were small—within 5% deviation, with minimal to no slip in the launch readiness date. However, as the U.S. Government Accountability Office (GAO) 2013 High-Risk Series update report (GAO, 2013) notes, “it may take several years to assess the effectiveness of NASA’s enhanced cost estimating practices,” and therefore, SMD will continue to rigorously maintain these practices and take additional steps to improve schedule and cost performance, particularly for large strategic missions like the Mars 2020 Rover and the Solar Probe Plus mission. These additional steps include ensuring that cost and schedule performance for all missions, regardless of mission size and scope, remain consistent with baseline commitments in order to maintain the overall balance of SMD’s portfolio.

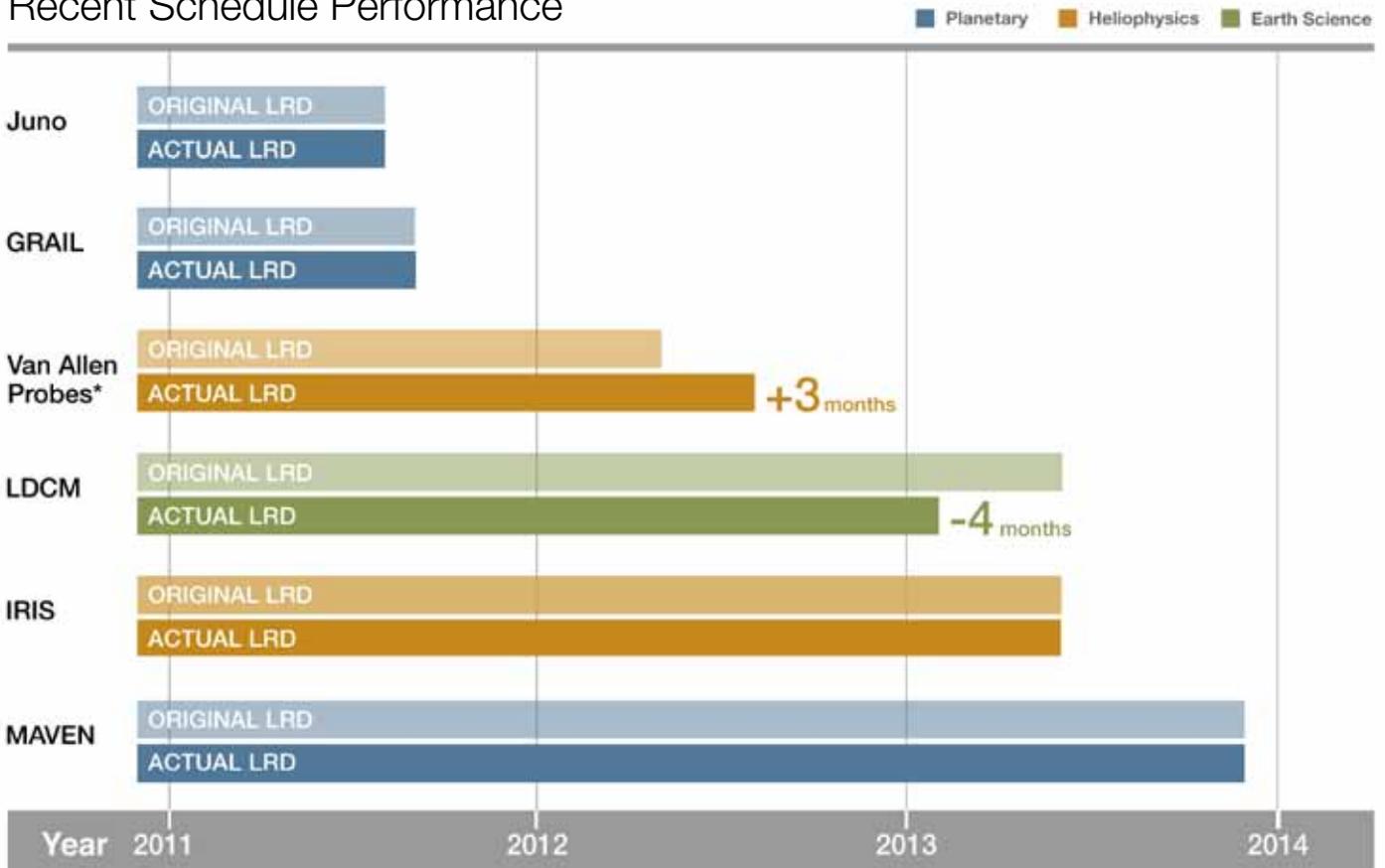
Figure 3.1 SMD missions that excelled in managing cost and schedule



*Formerly RBSP

Figure 3.1 (Continued) SMD missions that excelled in managing cost and schedule

Recent Schedule Performance



*Formerly RBSP

Although SMD has rigorously monitored its cost and schedule estimates over the last several years, the innovative nature of most space research missions and rising expendable launch vehicle (ELV) prices continue to cause the directorate to experience overruns. For example, an astrophysics project, the Gravity and Extreme Magnetism Small Explorer (GEMS), was not confirmed to proceed to the implementation phase. The decision not to proceed was made after an independent cost assessment found that there was a 50% chance the project would overrun by 20–30%. The James Webb Space Telescope (JWST) and the Mars Science Laboratory (MSL) are two other examples of missions that significantly overran projected cost and schedule estimates. An Agency priority, JWST was re-baselined in 2011 utilizing the new cost and schedule polices mentioned above, and continues to meet its cost and schedule commitments for a launch in 2018. MSL

launched in November 2011, with the Curiosity rover successfully landing on Mars in August 2012.

Since implementation of these efforts to control cost and schedule estimates, NASA has experienced significantly fewer cost and schedule overruns overall. One impact of the policy of budgeting at the 70% confidence level, however, has been to reduce the number of new mission starts. When missions do overrun, SMD endeavors to confine the impacts to the program in which that mission resides. Where that is not possible, SMD explores options such as reducing scope or cancelling the mission. When considering options for resolution, SMD takes into account cost, risk, and the advice of the scientific community, as obtained through the NAC Science Committee and its subcommittees.

Technology Development and Demonstration

Organizations managing complex, near-term development efforts perennially struggle to sustain investments in future capabilities. SMD has implemented technology programs in its science divisions, but in tight budgetary times, the organization finds it challenging to focus on technology developments needed to enable specific missions. NASA created the Space Technology Mission Directorate (STMD) in 2013 to develop space technologies needed by SMD and HEOMD, and to invest in strategic technologies potentially needed in the future. To continue to advance technology needed for its planned missions, SMD is collaborating and partnering with STMD across the full range of its nine technology programs (see Table 6.1 in chapter 6). Consultation and collaboration with STMD span all phases of technology development, and include activities such as identifying new opportunities, developing specific solicitations, partnering to co-fund technology developments, and reviewing and evaluating ongoing developments with a view toward technology infusion.

Impediments to International Collaboration on Space Missions

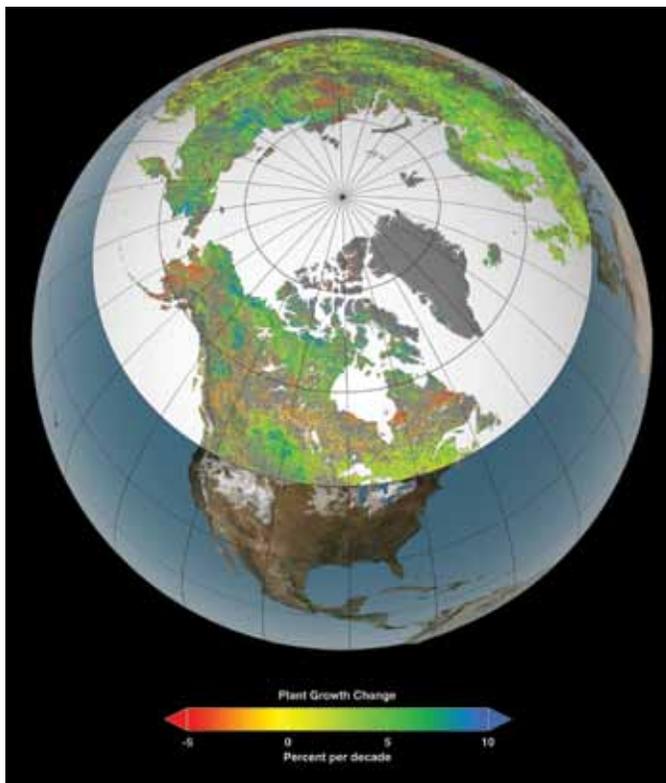
In 1999, Congress redefined civilian spacecraft as “defense articles” and transferred all aspects of controlling the export of information regarding their design, manufacture, and operation from the Department of Commerce Export Administration Regulations (EAR) to the State Department’s more restrictive International Traffic in Arms Regulations (ITAR). This change introduced a variety of serious legal and administrative complications into the conduct of international cooperative projects involving scientific spacecraft. By impeding the transfer of information on the design, fabrication, assembly, and operation of NASA spacecraft and instruments to foreign colleagues and foreign students and researchers at U.S. universities, ITAR impacts NASA’s ability to work with foreign space agencies and hampers the universities’ collaborative environment, which depends upon the open exchange of information and ideas among students and faculty. ITAR requires that individual Technical Assistance Agreements (TAAs) be established between the U.S. and each foreign entity working on a NASA program. For example, JWST has 210 individual TAAs in place, each

approved by the State Department. The executive and legislative branches worked collaboratively to overturn the 1999 statute with passage of the National Defense Authorization Act for Fiscal Year 2013, a prerequisite to considering any regulatory changes. The executive branch is publishing interim-final state and commerce regulations that resolve some of these concerns, particularly with regard to the scope of controlled ITAR activities. The issue of differentiating between scientific spacecraft and weapons, both of which rely on identical technology, is under further study as part of the interim-final regulations. The executive branch’s goal is to publish revised regulations in 2014 that further address these concerns.

Protecting the Planet While Advancing Science

SMD’s scientific research not only advances our understanding of the Earth and space, but the knowledge it generates informs the nation’s decision makers, first responders, and communities by providing observations and predictions on climate and extreme weather, space weather, and potentially hazardous near-Earth objects (NEOs). Many instruments and spacecraft platforms are beyond their prime design lifetimes, but are providing needed long-term measurements. Many space system assets that were originally designed to address research objectives are now being repurposed to gather measurements for operational use by NASA’s interagency and international partners, or to detect NEOs. Taking into consideration these challenges, the following details some of the activities we are engaging in to meet societal needs.

Climate and Sustained Land Imaging: Studying the Earth as a system is essential to understand the causes and consequences of climate change and other global environmental concerns. NASA’s Earth science programs evolve from an interdisciplinary view of the Earth, exploring the interaction among the atmosphere, oceans, ice sheets, land surface interior, and life itself. This approach enables scientists to measure the global effects of climate change and to inform decisions by governments, organizations, and people in the U.S. and around the world. The FY14 budget transfers responsibility for the sustained climate measurements of solar radiation, global ozone profiles, and Earth radiation balance from NOAA to NASA’s Earth



Satellite data in this visualization are from the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) instruments, which contribute to a vegetation index that allows researchers to track changes in plant growth over large areas. Of the 10 million square miles (26 million square kilometers) of northern vegetated lands depicted, 34 to 41 percent showed increases in plant growth (green and blue), 3 to 5 percent showed decreases in plant growth (orange and red), and 51 to 62 percent showed no changes (yellow) over the past 30 years. *Image Credit: NASA's Goddard Space Flight Center Scientific Visualization Studio*

Science Division, starting in the 2020 time frame. In addition, the FY14 budget initiates a new NASA project for the development of a sustained national system for global land imaging, to be developed in collaboration with USGS. These sustained global Earth observations are needed to monitor and study the Earth's climate system, land use, and land cover change, as well as to monitor the impact of weather and extreme weather events such as heat waves, cold waves, precipitation patterns, floods, droughts, and the intensity and distribution of tropical cyclones and tornadoes. Looking forward, under a likely scenario in which budgets remain relatively flat, maintaining a balance between providing the necessary uninterrupted climate measurements and developing new Earth system science

missions at the pace recommended in the decadal survey will be difficult. Furthermore, the need to establish an implementation strategy for the climate measurements and land imaging is critical to preventing a data gap in the long-term data sets for each.

Space Weather: Space weather refers to variable conditions on the Sun, in the solar wind, and in the near-space environment that can create risks for humans in space and cause disruption to electric power distribution and satellite operations, communications, and navigation. Heliophysics research provides a foundation to predict space weather events, mitigate the hazards posed to assets both in space and on the ground, and understand space weather impacts throughout the solar system. To meet national and societal space weather needs, NASA coordinates its space weather activities with several interagency and international partners, including NOAA, which is responsible for delivering operational space weather products and services to the nation. NASA's aging fleet of heliophysics spacecraft provide observations of solar and geophysical events that are incorporated into operational space weather forecasts and satellite anomaly assessments for national use. Specifically, space weather data from heliophysics spacecraft are provided either through direct broadcast from satellites or processed in near real time, and made accessible via the Internet. NASA also provides information for safe and efficient operation of its robotic and human missions, including situational awareness alerts and forecasts for NASA assets throughout the solar system. With the launch of the Deep Space Climate Observatory (DSCOVR) mission in 2015, the risk of losing the capability to conduct space weather measurements will be reduced. Other relevant NASA activities include pioneering new mission and instrument capabilities and improving space weather prediction algorithms and models.

Near-Earth Objects: Planetary science research programs and missions help advance our understanding of the formation of planetary bodies, the chemical and physical history of the solar system, and conditions that are capable of sustaining life. In addition, NASA's investments in planetary science protect Earth by identifying and characterizing celestial bodies and environments that may pose threats to our planet. In the future, NASA will conduct a bold new



Flying at an altitude of approximately 204 miles above Earth, the expedition 32 crew onboard the International Space Station (ISS) recorded a series of images of Aurora Australis on July 15, 2012. The Canadarm2 robot arm is in the foreground. *Image Credit: NASA*



This artist's concept shows the Wide-field Infrared Survey Explorer, or WISE spacecraft, in Earth orbit. WISE was decommissioned after it successfully completed its original astrophysics mission in 2011. In September 2013, engineers reactivated the mission to hunt for more asteroids and comets in a project called Near Earth Objects WISE, or NEOWISE. *Image Credit: NASA*

mission to redirect an asteroid to a stable lunar orbit, where astronauts will explore it to increase our understanding of NEOs and the resources they will provide for future human exploration beyond low Earth orbit (LEO). NASA leads the world in the detection and characterization of NEOs, and provides support for the ground-based observatories that are responsible for the discovery of about 98% of all known NEOs. NASA has also conducted robotic missions to study asteroids and comets. NASA uses radar techniques to better characterize the orbits, shapes, and sizes of observable NEOs, and funds research activities to better understand their composition and nature. NASA also funds the key reporting and dissemination infrastructure that allows for worldwide follow-up observations of NEOs, as well as related research activities, including the dissemination of information about NEOs to the larger scientific and engineering community. Consistent with the President's National Space Policy, NASA continues to collaborate with the Department of Defense and other government agencies on planning and exercises for responding to future hazardous NEOs.

National Science and Technology Workforce Development

Advances in science and technology are drivers for the nation's economic growth, leadership, and security. Enhancing the nation's research and development portfolio and maintaining its scientific capacity are essential if the U.S. is to maintain its competitiveness in the face of rapidly increasing international competition in high-tech industries. Continuing to support the entire scientific knowledge pipeline—from grade school, to postdoctoral programs, to opportunities for early-career scientists—will lead to a strong scientific workforce. SMD research, technology, and flight projects attract and train future science and technical workers at the undergraduate, graduate, and postdoctoral levels. These projects allow students and researchers to gain invaluable NASA science program work experience. The suborbital and small satellite programs (airplanes, sounding rockets, balloons, CubeSats, and future commercial suborbital platforms) and Principal Investigator-led missions enable students to participate in the entire lifecycle of a science mission, from design and construction, to flight and data

analysis. These hands-on opportunities provide experiences in problem solving and increase understanding of the systems engineering that is the underpinning of success within the broader scientific community. Specific programs such as the NASA Postdoctoral Program, NASA Earth and Space Science Fellowship (NESSF) Program, and other early-career programs (e.g., Early Career Fellowships, New Investigator Program in Earth Science, Roman Technology Fellowship Program, Hands-On Project Experience Program, and Student Airborne Research Program) ensure the continued training and nurturing of a highly qualified workforce. However, inadequate support for technical workforce development programs challenges the nation's ability to maintain the scientific capacity needed to drive innovation and economic growth in the future.

Long-term Program Planning

Establishment of long-term priorities and future program planning are essential for success in Earth and space science research, but are compromised by the lack of stable, long-term budget guidance that aligns with the timescales of space research missions and that is sufficient to fund a well-balanced portfolio. Long-term, continuous science measurements are essential for understanding how the Earth behaves as a system and the implications of the Sun's activity on Earth and on human and robotic explorers. Many of NASA's Earth science and heliophysics on-orbit spacecraft have outlived their original design lives, which threatens NASA's ability to continue delivering these valuable science data sets in the future. These long-lived spacecraft include: the Advanced Composition Explorer (ACE), Solar TERrestrial RElations Observatory (STEREO), Solar and Heliospheric Observatory (SOHO), and the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) mission, which supply heliophysics science data; Terra, Aqua, Aura, the Solar Radiation and Climate Experiment (SORCE), the Earth Observing-1 (EO-1) mission, Tropical Rainfall Measuring Mission (TRMM), and the Gravity Recovery and Climate Experiment (GRACE), which supply Earth science data; and many others that are operating beyond their prime mission lifetimes. Although these assets are accurately making essential science measurements, there is an increasing risk that if they malfunction prior to the launch of follow-on

spacecraft, valuable data will be lost and NASA's ability to maintain a long-term, continuous data record in key science areas will be inhibited. Furthermore, with the current and anticipated constrained budget, tradeoffs may need to be made across the various science research areas, potentially impacting the balance of programs and the opportunity to develop the workforce, especially early career scientists.

Unrealized Expectations

The budgetary environment has evolved since the release of the decadal surveys, and is very different from that assumed when the NRC formulated the survey recommendations. The overall budget level available to implement decadal survey recommendations—particularly future funding for new missions—is significantly reduced from that assumed in the decadal surveys. At the same time, the cost of doing business continues to rise with inflation, while the budget likely will experience limited growth, widening the gap even further between science community expectations for future missions and available resources. Appendix A identifies the status of the flight programs and missions that are included in the FY 2014 budget approved by Congress for SMD, and that respond to decadal survey recommendations and other national priorities.



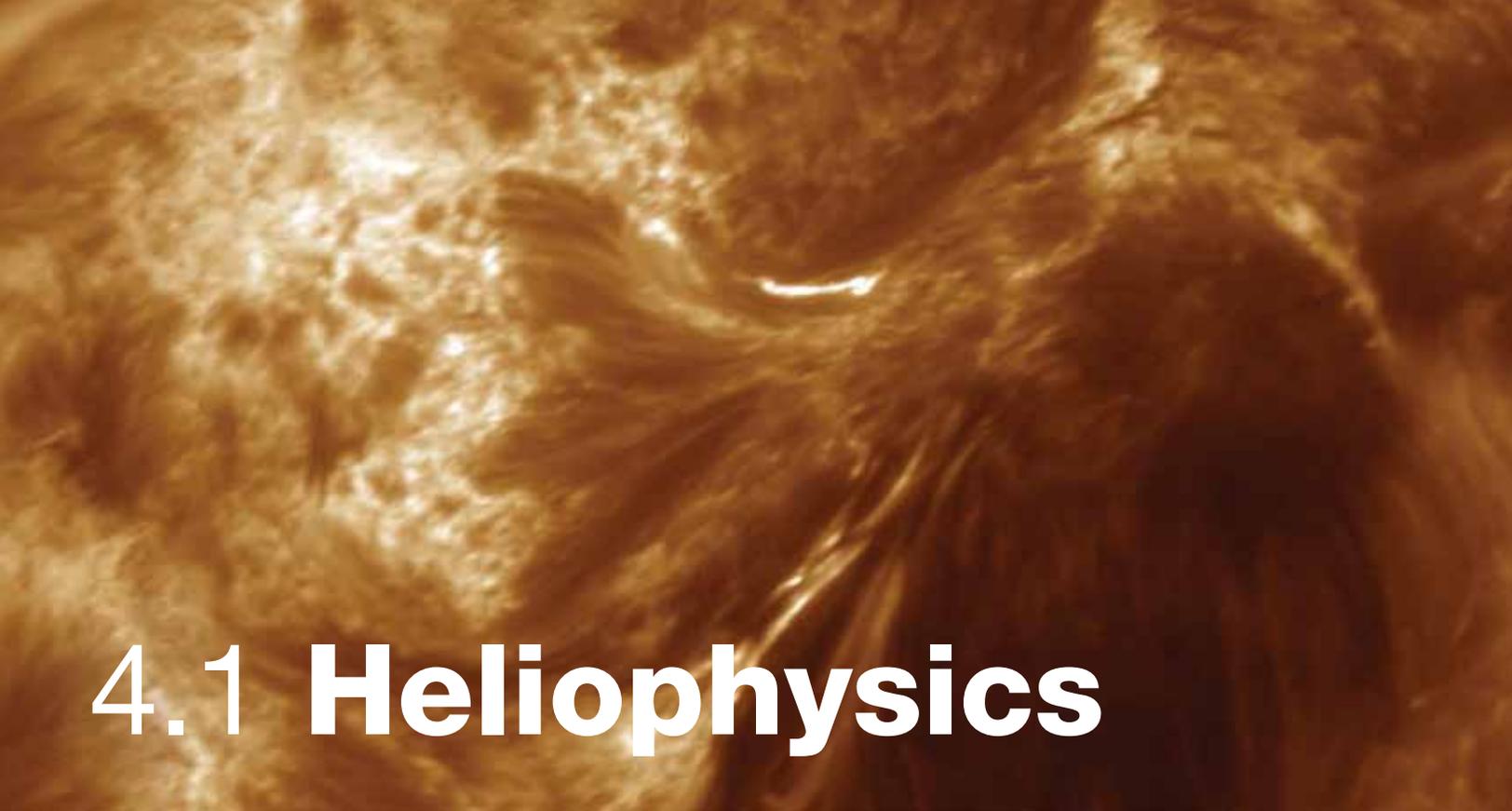
CHAPTER 4

Detailed Plans by Science Area

Based on national policy direction and recommendations from the nation's science community via NRC decadal surveys, each of the four SMD divisions has developed plans for future missions and supporting research and technology. Each of the four major sections to follow is devoted to a single science discipline, and identifies the top-level science questions to be pursued, the strategy to do so, and the current and planned future missions and research programs for the corresponding SMD science division.

The grouping of SMD research into these four science disciplines is a useful management construct, but the science itself knows no such boundaries. Indeed, important scientific opportunities exist in the regions of overlap among them, and across other NASA directorates and foreign and domestic agencies. Therefore, between each of the science sections in this chapter we highlight examples of such crosscutting efforts.

LEFT: This image of the Horsehead Nebula was taken in infrared light by the Hubble Space Telescope in honor of the 23rd anniversary of Hubble's launch. The rich tapestry of the Horsehead Nebula pops out against the backdrop of Milky Way stars and distant galaxies that are easily seen in infrared light.
Image Credit: NASA/STScI



4.1 Heliophysics

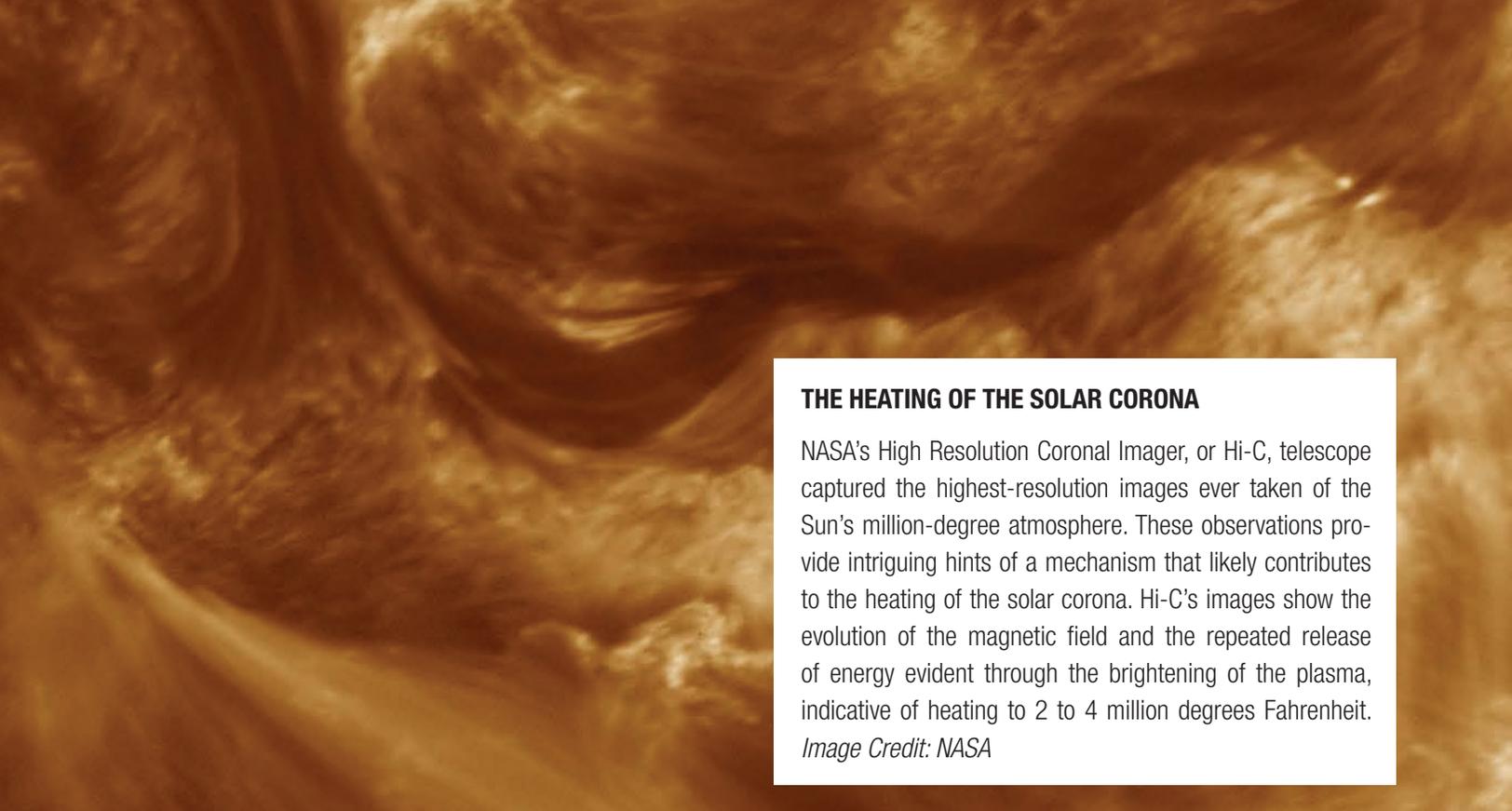
Strategy

Heliophysics encompasses science that improves our understanding of fundamental physical processes throughout the solar system, and enables us to understand how the Sun, as the major driver of the energy throughout the solar system, impacts our technological society. The scope of heliophysics is vast, spanning from the Sun's interior to Earth's upper atmosphere, throughout interplanetary space, to the edges of the heliosphere, where the solar wind interacts with the local interstellar medium. Heliophysics incorporates studies of the interconnected elements in a single system that produces dynamic space weather and that evolves in response to solar, planetary, and interstellar conditions.

All of NASA's space missions (including the inhabited ISS) and much of our nation's communications and navigation infrastructure (such as the critical Global Positioning System [GPS]) are operating in an environment driven by the highly variable output from the Sun. The Sun periodically sends out powerful coronal mass ejections and flares that accelerate charged particles to nearly the speed of light.

These disturbances drive the aurora and powerful electric currents on Earth, inflate the Van Allen radiation belts, violently churn the ionosphere and uppermost layers of the atmosphere, and can disrupt our technologies in space or be harmful to astronauts. NASA's heliophysics program provides the research and technological development necessary for the scientific understanding of how space weather affects human and robotic space exploration and the habitability of Earth and other worlds. The models and research tools NASA develops to interpret heliophysics data lead to substantial improvements in operational space weather monitoring.

Heliophysics uses our local space environment as a natural laboratory that can be directly probed with our satellites. Planets and solar systems are commonplace around other nearby stars and probably throughout the universe. The fundamental physical processes active in our near-space environment are also at work in these distant places humans cannot visit. Increasing understanding of our home in space therefore furthers humanity's knowledge of some



THE HEATING OF THE SOLAR CORONA

NASA's High Resolution Coronal Imager, or Hi-C, telescope captured the highest-resolution images ever taken of the Sun's million-degree atmosphere. These observations provide intriguing hints of a mechanism that likely contributes to the heating of the solar corona. Hi-C's images show the evolution of the magnetic field and the repeated release of energy evident through the brightening of the plasma, indicative of heating to 2 to 4 million degrees Fahrenheit.

Image Credit: NASA

of the most basic working principles of the universe. As exploration extends further into space, and as society's technological infrastructure is increasingly dependent on assets that are impacted by the space environment, a broader and fundamental understanding of these governing processes becomes ever more important and relevant.

The Agency's heliophysics strategic objective is to **understand the Sun and its interactions with Earth and the solar system, including space weather**. The heliophysics NRC decadal survey, *Solar and Space Physics: A Science for a Technological Society* (NRC, 2013), articulates the scientific challenges for this field of study and recommends a slate of design reference missions to meet them, to culminate in the achievement of a predictive capability to aid human endeavors on Earth and in space. The Heliophysics Division addresses its Agency objectives and the NRC decadal survey recommendations in the context of our national space policy by working to answer these fundamental science questions:

- What causes the Sun to vary?
- How do the geospace, planetary space environments and the heliosphere respond?
- What are the impacts on humanity?

To answer these questions, NASA's Heliophysics Division is implementing a program to achieve three overarching science goals:

- Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system
- Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system
- Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth

With substantial input from the heliophysics community, the NAC Science Committee Heliophysics Subcommittee has developed a Heliophysics science and technology roadmap (NAC Science Committee Heliophysics Subcommittee, 2014) to examine strategies for implementing the decadal survey recommendations. The Heliophysics science and technology roadmap provides the framework for guiding investment choices both on tactical and strategic scales and in the context of the decadal survey.

Challenges

The Heliophysics Division faces all the challenges articulated in chapter 3.3 (e.g., access to space, mission cost estimation and management, technology development and demonstration, impediments to international collaboration, long-term program planning). In particular, a constrained budget, combined with increasing costs associated with access to space, makes it impossible to implement all the decadal survey recommendations within the decade. In this environment, however, SMD's Heliophysics Division remains committed to implementing a balanced mission portfolio that provides the vitality needed to accomplish the breadth of the recent decadal survey's science goals within the limitations of its available resources.

In addition, the Heliophysics Division addresses system science that depends on coordinated observations made possible by the constellation of spacecraft that is made up of various scientific research missions, many of which are operating well beyond their design lifetimes. This constellation is known as the Heliophysics System Observatory (HSO). Maintaining and expanding the HSO requires continuing financial support, creating a natural conflict between continuing existing missions and other areas of the budget. In the coming years, as existing missions cease to operate, Heliophysics will be even more challenged by demands to provide the long-term and continuous observations necessary to understand the systemic nature of heliophysics science. If existing missions cease and are not replaced by missions providing similar measurements, potential synergies and opportunities enabled by the overlap of existing HSO measurements and measurements provided by new missions will not be realized. Consistent with the decadal survey recommendations, NASA is working with other agencies through the National Space Weather Program to

plan for continuing some solar and solar wind observations beyond the lifetime of current HSO assets.

The need for the connected measurements underscores the criticality of maintaining an adequate mission cadence and balance. Heliophysics will pursue multiple approaches to optimize the cadence by (1) applying state-of-the-art technologies to meet science goals at reduced expense, (2) optimizing the cost effectiveness of missions by fostering innovative mission designs, (3) leveraging domestic and international partnerships for missions and launch vehicles, and (4) adjusting the scope of the planned missions. The continuity of science measurements is key; without continuity, the opportunities provided by the simultaneous operation of the HSO elements and the new missions discussed here will be lost.

Implementation

The heliophysics science program consists of three flight programs including the Solar Terrestrial Probes (STP), Living With a Star (LWS), and Explorer Programs. In addition, the Heliophysics Research Program provides the theoretical and analytical foundation and tools that ensure new observations lead to scientific advancement. All of these elements contribute to the development of scientific understanding of the heliophysics system. Partnerships with other national and international agencies and within NASA provide additional opportunities to meet shared science goals. The teamwork between the U.S. and other space agencies augments the capabilities of many heliophysics science missions and permits investigations that could not be achieved separately. Additionally, given the constrained resource environment, the Heliophysics Division will continue to utilize the improved program/project mission cost estimation and management processes articulated in chapter 3.3, as well as integrate new mission management strategies recommended in the decadal survey, to contain cost and ensure successful and efficient implementation and operation of heliophysics programs.

The Heliophysics Division is working to rebalance its portfolio, where currently two-thirds of the budget is allocated to the LWS and STP flight programs and one-third is allocated to the Heliophysics Research and Heliophysics Explorer Programs, to a more equitable split as recommended by

the decadal survey. This rebalancing recognizes the combined contributions of the Heliophysics Research Program and the Principal Investigator (PI)-led Explorer Program to scientific advancement and discovery, and gives these programs higher priority.

Solar-Terrestrial Probes Program

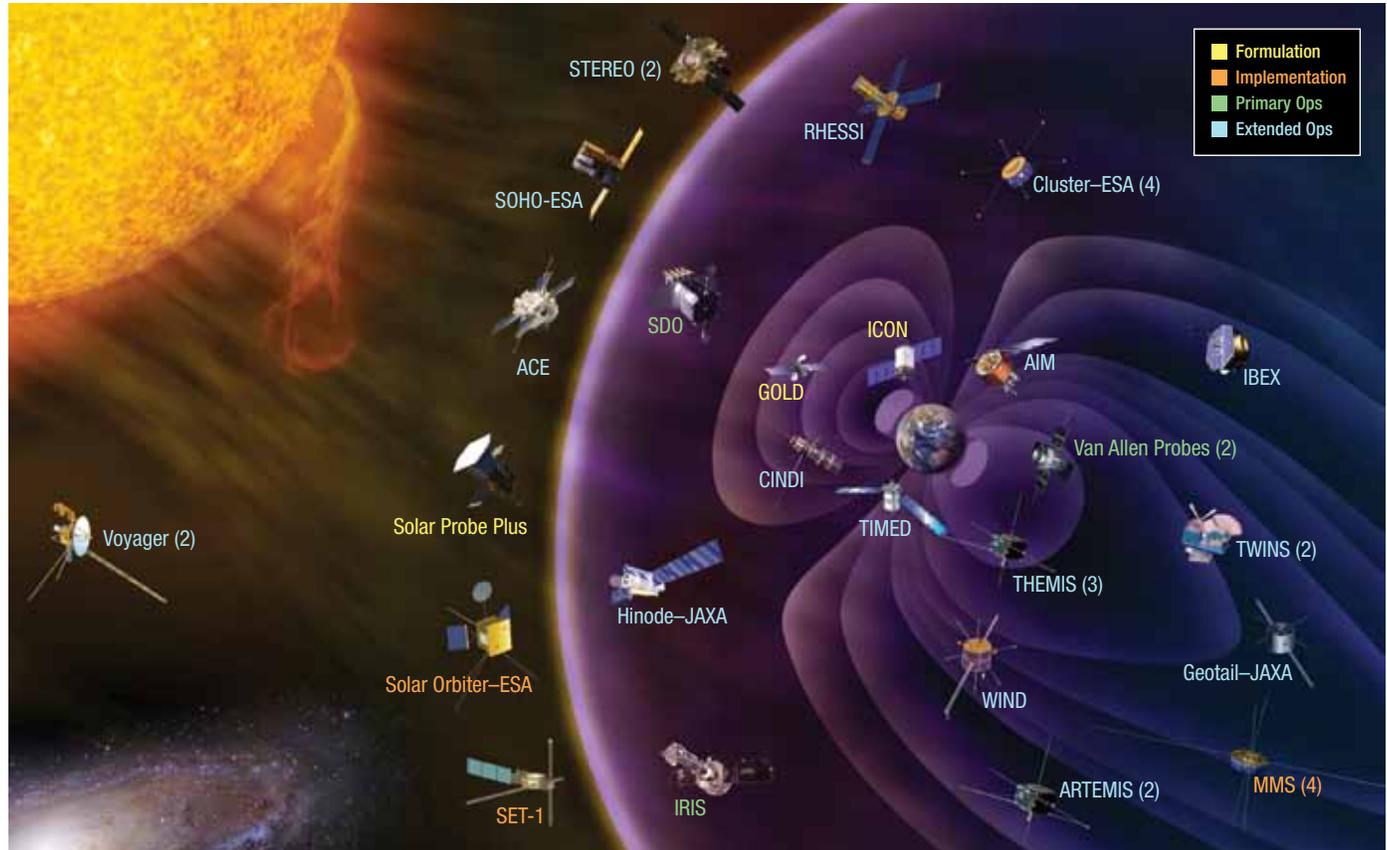
Missions within this program improve our understanding of fundamental physical processes that exist throughout the universe. Our stellar atmosphere contains rapidly flowing plasma—the solar wind—that creates a cavity in the galaxy called the heliosphere, which extends hundreds of times further than the distance between the Sun and the Earth. Because the Sun’s output is highly variable in location, intensity, and time, the near-space environment of the Earth and other planets is profoundly dynamic, and hosts numerous phenomena that can be examined in detail by instruments on spacecraft. We have in essence a laboratory in our own backyard for examining fundamental processes seen at

other planets and in other stellar settings. STP missions address unsolved scientific questions about critical physics that determines the mass, momentum, and energy flow within the interconnected Sun-heliosphere-Earth system. The knowledge gained from the focused science approach of the STP missions is critical to and enables the predictive capability addressed by the Living with a Star Program.

Living With a Star Program

This program emphasizes the science necessary to understand those aspects of the Sun and space environment that most directly affect life and society, and develops missions that help us better understand the coupled Sun-Earth system. The LWS missions adopt a systems approach toward understanding how major components of the connected Sun-heliosphere-Earth-planetary environment interact, with the ultimate goal of enabling a predictive capability. LWS missions are coupled with a targeted research program to answer the specific questions needed to understand the

Figure 4.1 NASA Heliophysics Missions



linkages among the interconnected systems that impact us. LWS science utilizes and augments the basic physics insights gained from the STP and Heliophysics Research Programs, applying them specifically to the science of space weather.

The LWS science component supports targeted research and technology investigations that address unresolved questions crossing the usual boundaries between scientific disciplines and research techniques. These investigations—particularly those that have an applied aspect, such as the science of space weather—develop specific, comprehensive models focused to understand heliophysics as a system. LWS also supports the comprehensive models required for development of a forecast capability for space weather. These strategic capability models are made available for use by the scientific community and for evaluation for potential transition to operational use at the Community Coordinated Modeling Center (CCMC) at NASA's Goddard Space Flight Center.

Heliophysics Explorer Program

The Explorer Program has a well-known history of providing high science return for a relatively small investment and is the highest priority for new missions within the decadal survey. The program complements the two strategic programs described above by providing a mix of small, medium, and large competitively selected PI-led missions required for a robust scientific flight program. Explorer missions have proven historically to be highly successful and cost-effective, providing insights into both the remotest parts of the universe and the detailed dynamics of Earth's local space environment. In combination with other HSO missions, the Explorer missions offer the opportunity to fill critical science gaps in the prescribed program and resolve many open science questions. By responding rapidly to new concepts and developments in science and forging synergistic relationships with larger-class strategic missions, Explorer missions play a major role in the ability of the Heliophysics Division to fulfill its NASA strategic objective. Priorities are based on an open competition of concepts solicited from the scientific community. The decadal survey emphasizes the importance of frequent flight opportunities for the Explorer missions, as well as the continued high scientific return of Missions of Opportunity (MoOs). The MoOs

are characterized by being part of a host space mission other than a strategic mission, and offer an extremely cost-effective platform for achieving science. A robust Explorer mission line is important to maintain current capabilities and will enable significant advances in our understanding of the field.

Heliophysics Research Program

The Heliophysics Research Program directly supports the generation of new knowledge, scientific and technological development, and scientific progress in different ways. Theory and numerical simulations, data analysis techniques, data modeling, and instrument development are fundamental areas of support. Laboratory work is needed to constrain and quantify basic physical processes, radiative transfer and magnetic reconnection being two examples. Low cost access to space is needed to develop the next generation of space hardware. The Heliophysics Division is committed to creating a robust research program by implementing growth as recommended by the decadal survey.

This growth will be achieved through the Diversify, Realize, Integrate, Venture, Educate (DRIVE) initiative. DRIVE is designed to more fully develop and effectively implement the entire Heliophysics Division portfolio of missions, experiments, simulations, and theoretical models. The DRIVE initiative can enhance the scientific return from our missions, develop new tools (both hardware and models), and reorganize our research program to better position itself for new scientific breakthroughs. To implement DRIVE, the division will need to focus resources on the most important and highest quality research and be more flexible in utilizing the full range of flight opportunities—sounding rockets, balloons, CubeSats, hosted payloads, etc.—to achieve the highest-priority science.

Competed research and analysis (R&A) is an important element of the Heliophysics Research Program as it enables utilization of the observational data brought in by HSO missions through open scientific competition. Groundbreaking science results lay the foundation for the formulation of a next generation of unanswered, more specific questions to be addressed by future missions. The R&A element uniquely fosters the system science of the HSO, enabling research that crosses mission boundaries. Competed R&A supports

instrument development and low-cost access to space that allow for a cost-effective, diversified way to develop the next generation of space hardware, train scientists and engineers, and make breakthrough science observations.

Another element of the Heliophysics Research Program encompasses development of advanced theories, models, and simulations and their verification through observations and data analysis. The CCMC, part of the Research Program, is the repository for these models and facilitates their validation.

Additional elements of the Heliophysics Research Program include ensuring the archiving and accessibility of all heliophysics observational data through support of archive facilities and openly competed innovative data distribution and display concepts. Other project lines within Heliophysics Research consist of the Sounding Rocket Program Office and the Wallops Research Range. Heliophysics manages these shared assets for the benefit of all SMD science divisions.

Heliophysics responded to the latest decadal survey by restructuring the Heliophysics Research Program to use resources more effectively and to tackle cross-disciplinary research problems. The Heliophysics-Grand Challenges Research (H-GCR) element supports larger PI-proposed team efforts that require a critical mass of expertise and utilize recent advances in computational power to make significant progress in understanding complex physical processes with broad importance. Previous discipline-specific opportunities were integrated into Heliophysics-wide opportunities, including the Heliophysics-Supporting Research (H-SR) element and the Heliophysics-Guest Investigator (H-GI) element. Results of H-SR investigations guide the direction and content of future science missions. H-GI is focused on maximizing the scientific return of missions in the HSO. The Heliophysics-Technology and Instrument Development for Science (H-TIDeS) element of the Research Program supports Low-Cost Access to Space (LCAS), which includes balloon, CubeSat, ISS, commercial reusable suborbital launch vehicles, and sounding rocket investigations. H-TIDeS also drives the development of instrument concepts that show promise for use on future heliophysics missions. The technological advances feed into future

missions and expand their effectiveness beyond current capabilities. The Laboratory Nuclear, Atomic and Plasma Physics sub-element supports advances in relevant laboratory measurements needed for the interpretation of current and future mission data. More information about H-TIDeS can be found in the Technology Development section below.

Current Missions

Using the entire fleet of solar, heliospheric, magnetospheric, ionospheric, and upper atmospheric missions, and data from planetary spacecraft, NASA operates the HSO as a distributed observatory to discover the larger scale and/or coupled processes at work throughout the complex system that makes up our space environment. This distributed observatory has flexibility and capabilities that evolve with each new mission launched. In addition to supplying valued science data, many operating HSO missions provide key observations used to predict space weather. Table 4.1 lists the missions in the currently operating HSO.

The HSO is a continuously evolving fleet, with each mission providing key inputs from unique vantage points. Examples include IRIS, the Van Allen Probes, STEREO, TIMED, and Voyager. IRIS observes how solar gases move, gather energy, and heat up through the interface region—information that is key to understanding what heats the Sun’s corona. IRIS improves our understanding of the interface region where most of the Sun’s ultraviolet emission (which impacts the near-Earth space environment and Earth’s climate) is generated. The twin Van Allen Probe spacecraft determine how charged particles in space near the Earth are stored and accelerated to hazardous energies that affect satellites, astronaut safety, and high-latitude aircraft. The first science result of the Van Allen Probes was the discovery of a long-lived relativistic electron storage ring embedded in Earth’s outer Van Allen belt. STEREO provided the first view of the whole Sun and three-dimensional views of coronal mass ejections, a major driver of space weather phenomena. TIMED provides a comprehensive overview of the variability of the mesosphere-lower thermosphere-ionosphere region of Earth’s atmosphere. Voyager 1 and 2 are at the edge of the heliosphere, exploring the interaction of the heliosphere with the local interstellar medium. Voyager 1 is now exploring interstellar space.

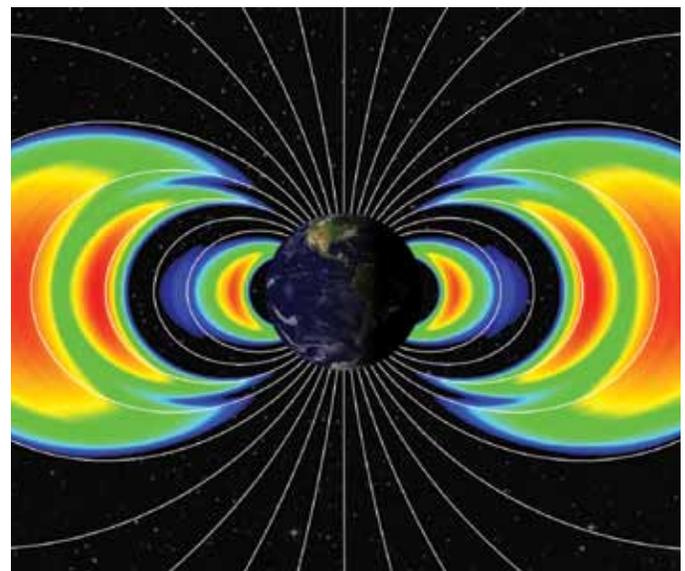
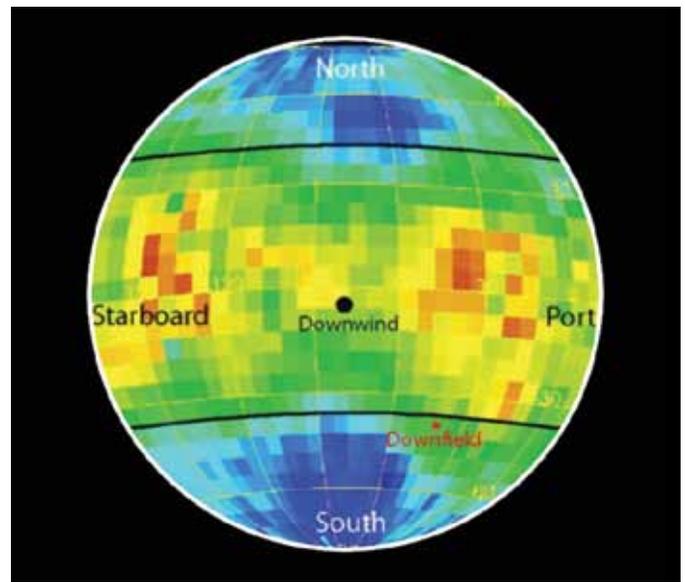
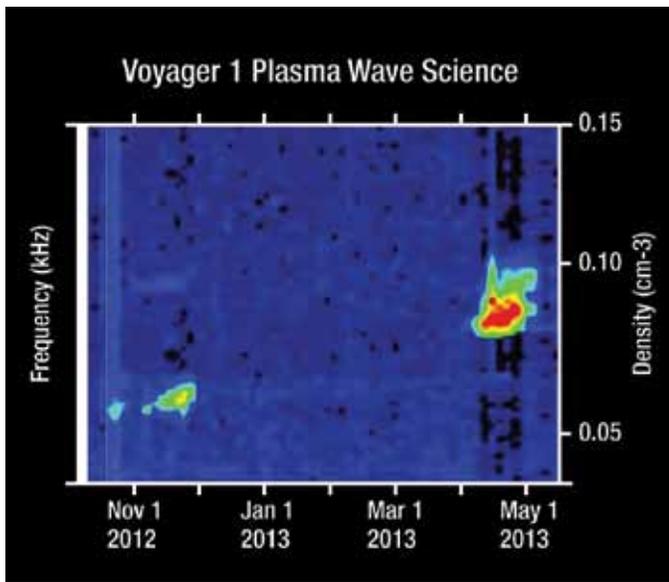
Table 4.1 Current Heliophysics Missions

Mission—Launch Year (Extended or Prime), Partners	Objective
Solar-Terrestrial Physics Program	
Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) —2001 (Extended)	SExplores the Earth’s Mesosphere and Lower Thermosphere (60–180 kilometers up), to understand the transfer of energy into and out of these regions and the basic structure that results from the energy transfer into the region.
Hinode (Solar B) —2006 (Extended) in partnership with Japan and the United Kingdom	Studies the generation, transport, and dissipation of magnetic energy from the photosphere to the corona to record how energy stored in the Sun’s magnetic field is released, either gradually or violently, as the field rises into the Sun’s outer atmosphere.
Solar Terrestrial Relations Observatory (STEREO) —2006 (Extended) in partnership with France, Switzerland, United Kingdom, Germany, Belgium, DOD	Traces the flow of energy and matter from the Sun to Earth with two space-based observatories. Reveals the 3D structure of coronal mass ejections and the reasons why they happen. STEREO observations are used for space weather forecasting by NOAA.
Living With a Star Program	
Solar Dynamics Observatory (SDO) —2010 (Prime)	Studies the creation of solar activity and how space weather results from that activity by measuring the Sun’s interior, magnetic field, the hot plasma of the solar corona, and solar spectral irradiance.
Van Allen Probes (Radiation Belt Storm Probes) —2012 (Prime) in partnership with Czech Republic	Use two identical spacecraft in elliptical orbits to provide an understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the Sun. It is anticipated that Van Allen Probes observations will be used for space weather “nowcasting” by NOAA.
Heliophysics Explorer Program	
Advanced Composition Explorer (ACE) —1997 (Extended)	Observes particles of solar, interplanetary, interstellar and galactic origins. Solar wind observations are used on an operational basis for space weather forecasting by both NOAA and USAF.
Reuven Ramaty High Energy Solar Spectroscope Imager (RHESSI) —2002 (Extended)	Advances our understanding of the fundamental high-energy processes at the core of the solar flare problem by imaging flares in x and gamma rays and obtaining a detailed energy spectrum at each point of the image.
Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) —2006 and 2008 (Extended) in partnership with National Reconnaissance Office (NRO), Germany	Enables the 3-D visualization and the resolution of large scale structures and dynamics within the magnetosphere by imaging the charge exchange of neutral atoms over a broad energy range, using two identical instruments on two widely spaced high-altitude, high-inclination spacecraft
Time History of Events and Macroscale Interactions during Substorms (THEMIS) —2007 (Extended) in partnership with Germany, France, and Austria	Originally used five identically instrumented spacecraft to answer questions concerning the nature of the sub-storm instabilities that abruptly and explosively release solar wind energy stored within the Earth’s magnetotail. Two of the five spacecraft have been re-purposed as the ARTEMIS mission to study the space weather environment around the Moon.
Aeronomy of Ice in the Mesosphere (AIM) —2007 (Extended)	Explores Polar Mesospheric Clouds, which form an icy membrane at the edge of Earth’s atmosphere, to find out why they form and why they are changing

Table 4.1 (Continued) Current Heliophysics Missions

Mission—Launch Year (Extended or Prime), Partners	Objective
Heliophysics Explorer Program (Continued)	
Aeronomy of Ice in the Mesosphere (AIM) —2007 (Extended)	Explores Polar Mesospheric Clouds, which form an icy membrane at the edge of Earth's atmosphere, to find out why they form and why they are changing
Coupled Ion-Neutral Dynamics Investigation (CINDI) —2008 (Extended) in partnership with USAF	Uncovers the role of ion-neutral interactions in the generation of small and large-scale electric fields in the Earth's upper atmosphere.
Interstellar Boundary Explorer (IBEX) —2008 (Extended) in partnership with Switzerland	Measures energetic neutral atoms created at the boundary that separates our heliosphere from the local interstellar medium, giving us the first evolving images of the heliosphere's outer edge and surroundings.
Interface Region Imaging Spectrograph (IRIS) —2013 (Prime) in partnership with Norway	Increases our understanding of energy transport into the corona and solar wind and provides an archetype for all stellar atmospheres by tracing the flow of energy and plasma through the chromosphere and transition region into the corona using spectrometry and imaging.
Heliophysics Research Program*	
Voyager —1977 (Extended)	The Voyager Interstellar Mission explores the outer heliosphere, heliosheath and now the interstellar medium with plasma, energetic particle, magnetic field and plasma wave instrumentation. Among them, the two Voyagers hold the records of the longest-operating and the most distant spacecraft.
Geotail —1992 (Extended) in partnership with Japan	Studies the dynamics of the Earth's magnetotail over a wide range of distances and measures global energy flow and transformation in the magnetotail.
Wind —1994 (Extended) in partnership with France	Measures solar radio bursts, solar wind and energetic particle properties, and complements ACE near the Lagrange 1 (L1) point. It also supports investigations of Gamma ray bursts in tandem with the Astrophysics SWIFT Gamma-ray Explorer mission.
Solar and Heliospheric Observatory (SOHO) —1995 (Extended) in partnership with ESA	Studies the internal structure of the Sun, its extensive outer atmosphere and the origin of the solar wind and solar energetic particles. SOHO observations are used for space weather forecasting by NOAA.
Cluster-II —2000 (Extended) in partnership with ESA	The four identical Cluster II satellites study the impact of the Sun's activity on the Earth's space environment by flying in formation around Earth. For the first time in space history, this mission is able to collect three-dimensional information on how the solar wind interacts with the magnetosphere and affects near-Earth space and its atmosphere, including aurorae.

* Missions listed either existed before or were part of an international partnership outside the current Heliophysics Division's implementation structure.



TOP: Voyager 1's plasma wave instrument detected vibrations of dense interstellar plasma, or ionized gas, from October to November 2012 and April to May 2013. The graphic shows the frequency of the waves, which indicates the density of the plasma. *Image Credit: NASA/JPL-Caltech/University of Iowa*

BOTTOM: This artist's concept depicts NASA's Voyager 1 spacecraft entering interstellar space, or the space between stars. *Image Credit: NASA/JPL-Caltech*

TOP: NASA's Interstellar Boundary Explorer (IBEX) recently mapped the boundaries of the solar system's tail (the heliotail). This data from IBEX shows what it observed looking down the heliotail. The yellow and red colors represent areas of slow-moving particles, and the blue represents the fast-moving particles. *Image Credit: NASA/IBEX*

BOTTOM: A new radiation belt has been discovered above Earth; it is shown here using actual data as the middle arc of orange and red of the three arcs seen on each side of the Earth. The new belt was observed for the first time by Relativistic Electron Proton Telescopes (REPT) flying on NASA's twin Van Allen Probes. *Image Credit: NASA*

To obtain the greatest science benefits possible within the division’s resources, the Heliophysics Division collaborates with other national or international agencies’ missions whenever possible. The division routinely partners with other agencies to fulfill space weather research needs and provides input for the operational objectives of the nation. Examples include the real-time space weather data supplied by the ACE, STEREO, SOHO, Van Allen Probes, and SDO missions. The division also utilizes the considerable synergies between heliophysics and other science disciplines. For example, the SDO was a high priority in the 2002 astrophysics decadal survey, as the Sun is an archetype for all similar stars, and the Planetary Science Division’s Juno mission fulfills the third-priority mid-scale mission recommendation in the 2003 heliophysics decadal survey. The two ARTEMIS (Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon’s Interaction with the Sun) probes were re-purposed from the THEMIS

(Time History of Events and Macroscale Interactions during Substorms) mission to orbit the Moon’s surface and provide new information about the lunar internal structure, plasma, and radiation environment.

Missions in Formulation and Development

The heliophysics missions now in formulation or development for launch over the next decade address some of the priorities in both the 2003 and 2012 Heliophysics decadal surveys. These missions include the Magnetospheric Multiscale (MMS,) Solar Orbiter Collaboration (SOC), and Solar Probe Plus (SPP). The newly selected Explorer mission, Ionospheric Connection (ICON), together with the newly selected MoO, Global-scale Observations of the Limb and Disk (GOLD), will focus on the dynamics of the ionosphere. Table 4.2 identifies the missions that are in formulation or

Table 4.2 Heliophysics Missions in Formulation or Development

Mission—Launch Year (Extended or Prime), Partners	Objective
Solar-Terrestrial Physics Program	
Magnetospheric Multiscale (MMS) —2015 in partnership with Austria, France, Japan and Sweden	Consists of four identically instrumented spacecraft that will use Earth’s magnetosphere as a laboratory to study the microphysics of three fundamental plasma processes: magnetic reconnection, energetic particle acceleration, and turbulence.
Living With a Star Program	
Space Environment Testbeds (SET-1) —2016 in partnership with United Kingdom, France, and the U.S. Air Force	Improve the engineering approach to accommodate and / or mitigate the effects of solar variability on spacecraft design and operations, specifically demonstrate improved hardware performance in the space radiation environment.
Solar Orbiter Collaboration (SOC) —NLT 2018* in partnership with ESA	Study the Sun from a distance closer than any spacecraft previously has. This mission will explore the inner solar system from high latitudes to improve the understanding of how the Sun determines the environment of the inner solar system and how fundamental plasma physical processes operate near the Sun. To answer these questions, it is essential to make in-situ measurements of the solar wind plasma, fields, waves, and energetic particles close enough to the Sun that they are still relatively unprocessed, and to connect the in situ measurements with remote sensing of the near-Sun atmosphere.
Solar Probe Plus (SPP) —2018 in partnership with France, Germany, and Belgium	The SPP will fly into the Sun’s atmosphere (or corona) and employ a combination of in-situ measurements and imaging to achieve the mission’s primary scientific goal: to understand how the Sun’s corona is heated and how the solar wind is accelerated. SPP will revolutionize our knowledge of the physics of the origin and evolution of the solar wind.

* Reflects the Agency baseline commitment to launch no later than (NLT) the year identified.

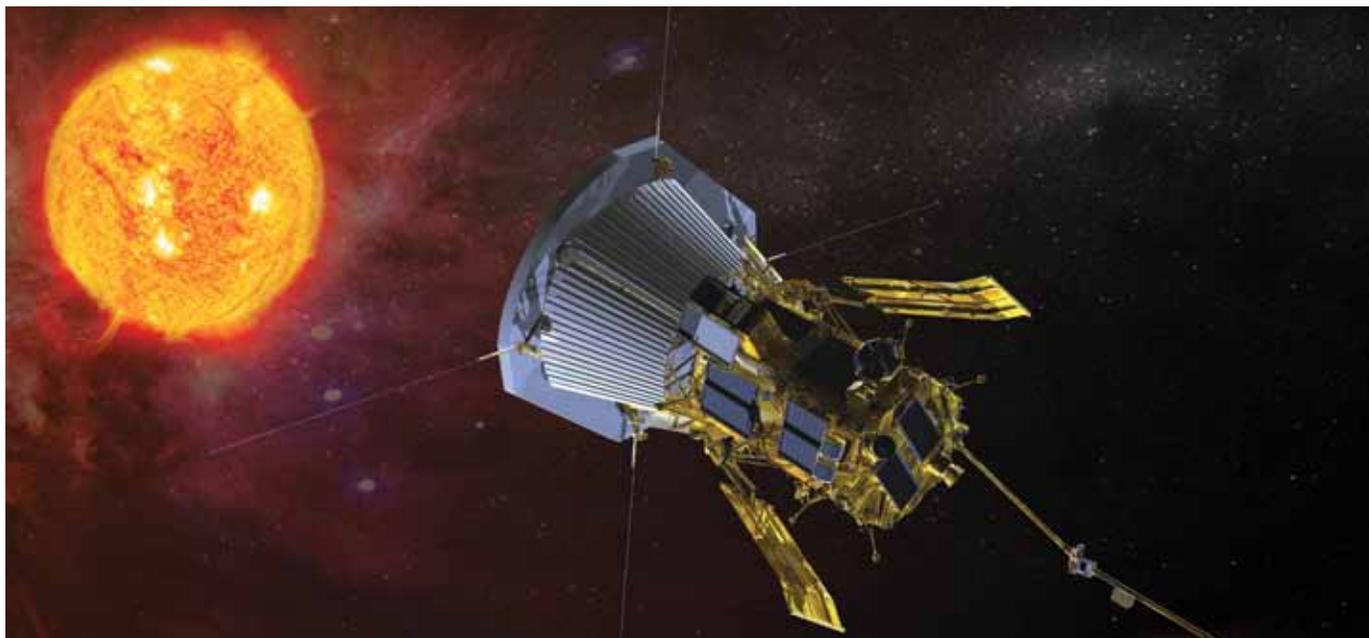
Table 4.2 (Continued) Heliophysics Missions in Formulation or Development

Mission—Launch Year (Extended or Prime), Partners	Objective
Heliophysics Explorer Program	
Ionospheric Connection (ICON) —2017 in partnership with Belgium	ICON will explore the boundary between Earth and space to understand the physical connection between our world and our space environment. ICON will employ a revolutionary concept of combining remote optical imaging and in situ measurements of the plasma at points where these are tied together by Earth’s magnetic field. With these measurements, ICON will simultaneously retrieve all of the properties of the system that both influence and result from the dynamical and chemical coupling of the atmosphere and ionosphere.
Global-scale Observations of the Limb and Disk (GOLD) —2017	The GOLD mission of opportunity will fly an ultraviolet imaging spectrograph on a geostationary satellite to measure densities and temperatures in Earth’s thermosphere and ionosphere. GOLD will perform unprecedented imaging of the weather of the upper atmosphere and examine the response of the upper atmosphere to forcing from the Sun, the magnetosphere and the lower atmosphere.

development, with launches planned over the 2014–2020 timeframe. The expected launch years are subject to change, but provide the relative timeframes for development.

Another upcoming mission in the STP Program is the MMS mission, a four-spacecraft constellation designed to use

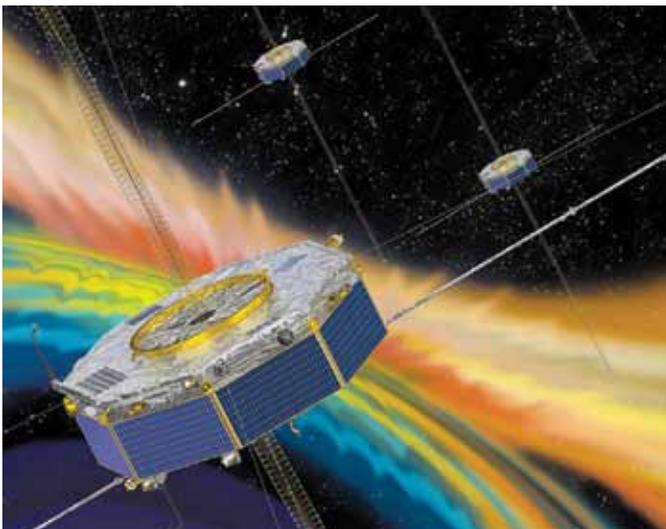
Earth’s magnetosphere as a laboratory to study the micro-physics of magnetic reconnection, a fundamental process that converts magnetic energy into heat and acceleration of charged particles. Magnetic reconnection occurs in all astrophysical plasma systems, but can be studied in detail in our solar system and most efficiently in Earth’s magnetosphere.



Artist’s impression of SPP, its solar panels folded into the shadows of its protective shield, gathering data on its approach to the Sun. As SPP approaches the Sun, its revolutionary carbon-composite heat shield must withstand temperatures exceeding 2,550 degrees Fahrenheit and blasts of intense radiation. *Image Credit: NASA/John Hopkins University/Applied Physics Laboratory*



TOP: The four MMS spacecraft are stacked in preparation for vibration testing. *Image Credit: NASA/GSFC*



BOTTOM: This artist's concept depicts three of the four identical MMS mission spacecraft. *Image Credit: NASA/JPL-Caltech*

SOC is a collaborative mission with ESA that will provide close-up views of the Sun's polar regions, which are poorly observed from Earth.

SPP will be the first mission to visit a star. The mission will study the streams of charged particles the Sun hurls into space from an unprecedented vantage point: inside the Sun's corona—its outer atmosphere—where the processes that heat the corona and produce solar wind occur. At its closest approach, SPP will zip past the Sun at 125 miles per second, protected by a carbon-composite heat shield that must withstand up to 2,500 degrees Fahrenheit and survive blasts of radiation and energized dust at levels not experienced by any previous spacecraft. By directly probing the solar corona, this mission will revolutionize our knowledge and understanding of coronal heating and of the origin and acceleration of the solar wind, critical questions in heliophysics that have been ranked as top priorities for decades. By making the first direct, in situ measurements of the region where some of the most hazardous solar particles are energized, SPP will make a fundamental contribution to our ability to characterize and forecast the radiation environment in which future space explorers will work and live.

Future Missions

The Heliophysics NRC decadal survey was completed in 2012 and formed the basis for the 2014 Heliophysics science and technology roadmap. To achieve the science goals of the Heliophysics Division, the roadmap recommends a strategy that leverages all program elements of the Heliophysics Division. The recommendations include new missions to be deployed by the Explorer, STP, and LWS mission lines, establishing a queue of science targets as shown in Table 4.3. These targets address the most compelling science questions in heliophysics and provide several new opportunities for discovery. The division's research strategy is based upon prioritized, yet flexible, science goals.

Table 4.3 Heliophysics Future Missions

Mission—Launch Year (Extended or Prime), Partners	Objective
Solar-Terrestrial Physics Program	
Heliospheric Boundary and Solar Wind Plasma Mission—2022	Advance our understanding of the interstellar boundary and its interaction with the interstellar medium through remote sensing observation and unravel the mechanisms by which particles are energized.
Lower Atmosphere Driving Mission—2025	Understand how lower atmospheric wave energy drives the variability and structure of the near-Earth plasma.
Magnetosphere-Ionosphere-Thermosphere Coupling Mission—2033	Determine how the magnetosphere-ionosphere-thermosphere system is coupled and responds to solar and magnetospheric forcing.
Living With a Star Program	
Geospace Dynamics Coupling Mission—2030	To characterize and understand the tightly coupled ionosphere-atmosphere as a regulator of nonlinear dynamics in the geospace system.
Heliophysics Explorer Program	
Explorers and Missions of Opportunity—2020, 2023, 2026, 2029	High priority science investigations, filling focused, but critical gaps in our knowledge

Technology Development

Significant progress toward meeting the scientific and technical challenges for heliophysics over the coming decades hinges on improving observational capabilities and innovative instrumentation. The Heliophysics Division supports development of technologies for its flight missions via mission-specific elements through the flight programs and the newly initiated Heliophysics Technology and Instrument Development for Science (H-TIDeS) element of the Heliophysics Research Program.

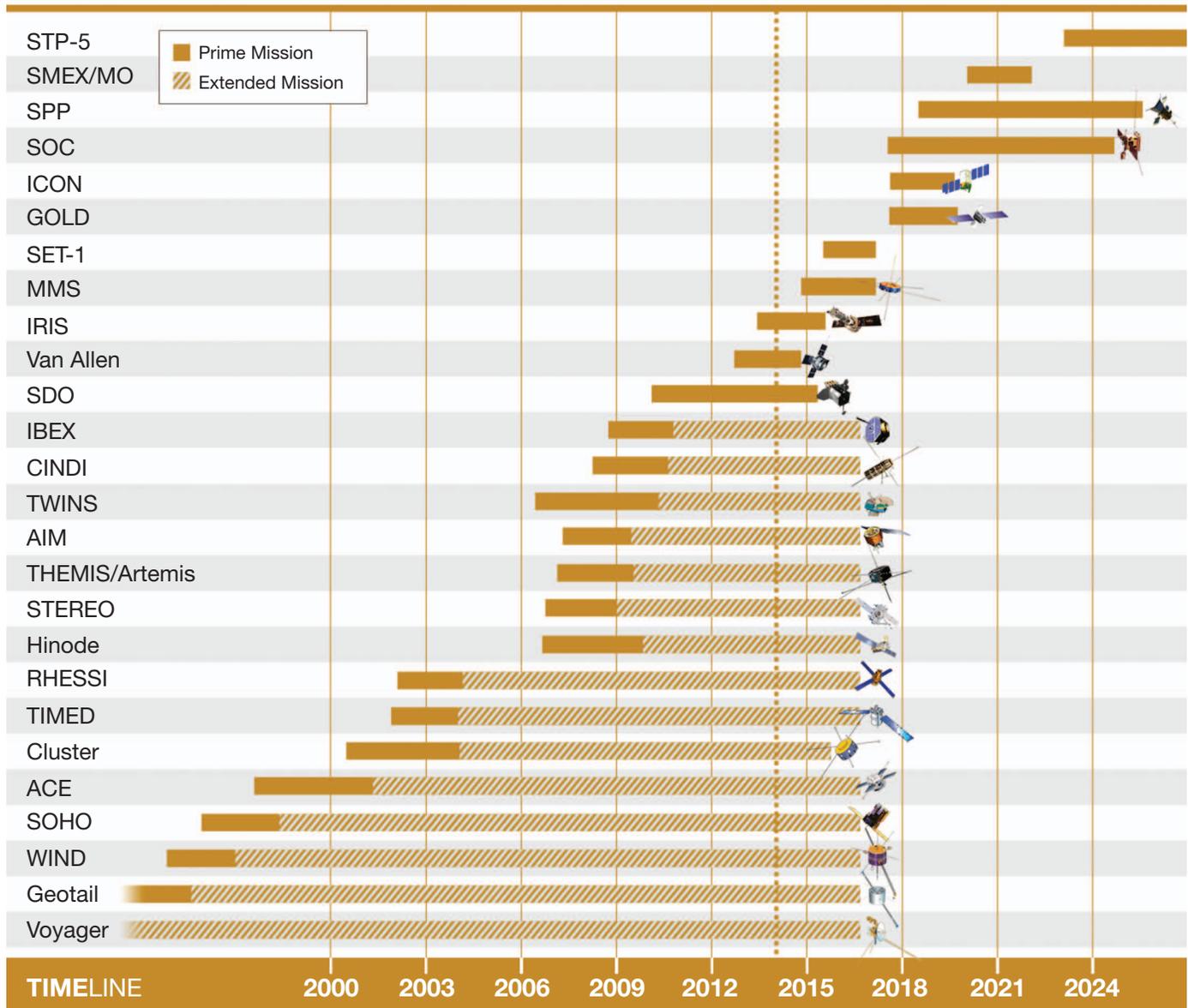
Heliophysics flight program lines develop medium technology readiness level (TRL) technologies, bringing specific technologies into maturation as required by the mission. For example, technologies developed to enable the SPP mission to fly 20 times closer to the Sun than the Earth and to receive 500 times the solar input are representative of this concept. Key technologies developed for this challenging mission include instruments and a revolutionary carbon-carbon composite heat shield to withstand temperatures over 2500 degrees Fahrenheit.

H-TIDeS unifies our development of low- to medium-TRL technologies, as well as instrument feasibility studies and proof of concept efforts. This element of our research program consists of competitive PI-led efforts, awarded via a peer review process based on the science and technical merits of the submitted proposals, and according to the science priorities of the Heliophysics Division as set by the decadal survey. Examples of areas funded through H-TIDeS include X-ray and Gamma-ray detectors, extreme ultraviolet mirror coatings, X-ray optics, high-energy particle detectors, energetic neutral atom detectors, and new nano-dust analyzers.

Small satellites, including CubeSats, have tremendous promise in addressing many heliophysics science objectives. Although small satellite technologies have advanced rapidly over the last few years, significant technological hurdles still remain. H-TIDeS is supporting the development of a number of instrument technologies (e.g., low mass particle spectrometers, and compact interferometers) and

Figure 4.2 Summary of Heliophysics Science Missions

Heliophysics Timeline



The extended missions depicted in Figure 4.2 are approved for continued operations based on a senior peer review conducted by scientists every two years to determine the scientific value and priority of further mission extensions.

working across the Agency to develop the underlying infrastructure. Examples of Agency-wide partnerships for small satellites include investments made by STMD and HEOMD in developing launch systems such as the CubeSat Launch

Initiative (CSLI) and deep space operations such as the first test flight, Exploration Mission (EM)-1, of the Space Launch System (SLS). The Heliophysics Division is well poised to take advantage of this new technology.



An aurora on March 8, 2012, shimmering over snow-covered mountains in Faskrudsfjordur, Iceland. *Image Credit: Jónína Óskarsdóttir*

Crosscutting Applications of **Heliophysics** **Science**

The term “space weather” refers to variable conditions on the Sun, in the solar wind, and in the near-space environment that can create risks for humans in space and cause disruption to electric power distribution on Earth and satellite operations, communications, and navigation. Modern society depends on a variety of technologies susceptible to the extremes of space weather. Strong electrical currents driven along the Earth’s surface during geomagnetic events disrupt electric power grids and contribute to the corrosion of oil and gas pipelines. Changes in the ionosphere during geomagnetic storms interfere with high-frequency radio communications and GPS navigation. Exposure of spacecraft to energetic solar particles can cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind systems such as imagers, star trackers, and scientific instrumentation. Given the growing importance of space to our nation’s economic well-being and security, it is of increasing importance that NASA and its partner agencies continue to advance our nation’s capability to understand and predict space weather events.

Space weather forecasting in interplanetary space is crucial to NASA’s human and robotic exploration objectives beyond Earth’s orbit. Eventually, astronauts will travel to distant places where natural shielding like Earth’s magnetic field is absent. NASA’s plans to send astronauts to asteroids and Mars safely rely on our ability to successfully understand and predict space weather. Protection of humans in space is an operational activity within NASA’s HEOMD. SMD collaborates with HEOMD’s Space Radiation Analysis Group at NASA’s Johnson Space Center, which is directly responsible for ensuring that the radiation exposure of astronauts remains below established safety limits.

In support of NOAA satellites and to enable NOAA to fulfill its responsibility for delivering operational space

weather forecasts and products to the nation, NASA research spacecraft (e.g., ACE, STEREO, SOHO, SDO, and Van Allen Probes missions) supply real-time space weather data. Other partnerships include the CINDI instrument NASA supplied for an Air Force satellite, and TWINS-A & B the Agency provided for two National Reconnaissance Office satellites. NASA will continue to cooperate with other agencies to enable new knowledge in this area and to measure conditions in space critical to both operational and scientific research.

Interagency coordination of space weather activities has been formalized through the National Space Weather Program Council, which is hosted by the Office of the Federal Coordinator for Meteorology. This multiagency organization comprised of representatives from ten federal agencies functions as a steering group responsible for tracking the progress of the National Space Weather Program. External constituencies requesting and making use of new knowledge and data from NASA’s efforts in heliophysics include NOAA, the Department of Defense, and the Federal Aviation Administration.

Space weather is of international importance and NASA is the U.S. representative at the United Nations (UN) Committee on the Peaceful Uses of Outer Space (UNCOPUOS) for space weather matters. This responsibility includes leadership of the International Space Weather Initiative (ISWI), a UN initiative to advance space weather science by establishing a global space weather data and modeling network. NASA also serves on the Steering Committee of the International Living with a Star (ILWS), which includes 31 space agencies worldwide. ILWS provides world leadership for the coordination of solar and space physics missions, observations, and understanding.



4.2 Earth Science

Strategy

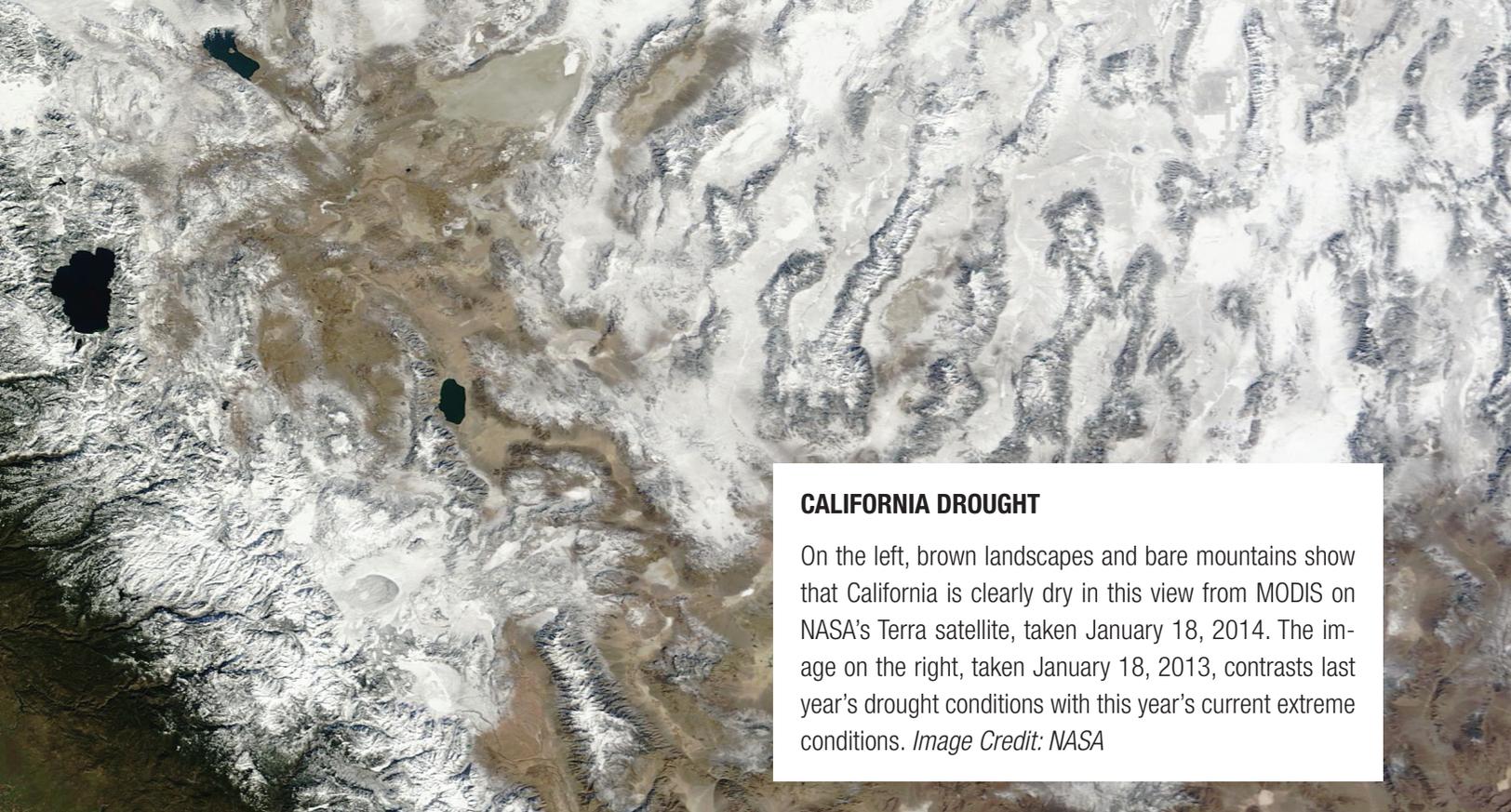
Our planet is changing on all spatial and temporal scales and studying the Earth as a complex system is essential to understanding the causes and consequences of climate change and other global environmental concerns. The purpose of NASA's Earth science program is to advance our scientific understanding of Earth as a system and its response to natural and human-induced changes and to improve our ability to predict climate, weather, and natural hazards.

NASA's ability to observe global change on regional scales and conduct research on the causes and consequences of change position it to address the Agency strategic objective for Earth science, which is to **advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet**. NASA addresses the issues and opportunities of climate change and environmental sensitivity by answering the following key science questions through our Earth science program:

- How is the global Earth system changing?
- What causes these changes in the Earth system?
- How will the Earth system change in the future?
- How can Earth system science provide societal benefit?

These science questions translate into seven overarching science goals to guide the Earth Science Division's selection of investigations and other programmatic decisions:

- Advance the understanding of changes in the Earth's radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition (*Atmospheric Composition*)
- Improve the capability to predict weather and extreme weather events (*Weather*)
- Detect and predict changes in Earth's ecosystems and biogeochemical cycles, including land cover, biodiversity, and the global carbon cycle (Carbon Cycle and Ecosystems)



CALIFORNIA DROUGHT

On the left, brown landscapes and bare mountains show that California is clearly dry in this view from MODIS on NASA's Terra satellite, taken January 18, 2014. The image on the right, taken January 18, 2013, contrasts last year's drought conditions with this year's current extreme conditions. *Image Credit: NASA*

- Enable better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change (*Water and Energy Cycle*)
- Improve the ability to predict climate changes by better understanding the roles and interactions of the ocean, atmosphere, land and ice in the climate system (*Climate Variability and Change*)
- Characterize the dynamics of Earth's surface and interior, improving the capability to assess and respond to natural hazards and extreme events (*Earth Surface and Interior*)
- Further the use of Earth system science research to inform decisions and provide benefits to society

Two foundational documents guide the overall approach to the Earth science program: the NRC's 2007 Earth sci-

ence decadal survey and NASA's 2010 climate-centric architecture plan.

The NRC decadal survey articulates the following vision for Earth science research and applications in support of society:

Understanding the complex, changing planet on which we live, how it supports life and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important challenges for society as it seeks to achieve prosperity, health, and sustainability.

The 2007 decadal survey recommended a broad portfolio of missions to support the research that is needed to provide answers to the key science questions and accomplish the related science goals. Recognizing the pressing challenge of climate change, NASA addressed the need to ensure

the continuity of key climate monitoring measurements in its 2010 climate-centric architecture plan. The plan reflects the need to collect additional key climate monitoring measurements, which are critical to informing policy and action, and which other agencies and international partners had not planned to continue. The plan also accelerated key decadal survey recommendations to address the nation's climate priorities.

NASA's ability to view the Earth from a global perspective enables it to provide a broad, integrated set of uniformly high-quality data covering all parts of the planet. NASA shares this unique knowledge with the global community, including members of the science, government, industry, education, and policy-maker communities. For example, NASA plays a leadership role in a range of federal interagency activities, such as the USGCRP, by providing global observations, research results, and modeling capabilities. It also maintains an expansive network of partnerships with foreign space agencies and international research organizations to conduct activities ranging from data sharing agreements to joint development of satellite missions. These interagency activities and international partnerships substantially leverage NASA's investments and provide knowledge essential for understanding the causes and consequences of climate change and other global environmental concerns.

Challenges

NASA is facing the growing challenge of continuing to advance Earth systems science (including research endeavors, observational capabilities, and data systems) while simultaneously addressing increasing demands to provide sustained climate observations.

Data-related issues are another growing challenge. As explained in the Agency's 2010 climate-centric architecture plan, "many existing system components and functions need to be updated and improved, driven by challenging new requirements. Data rates and data volumes will increase dramatically." Further, the decadal survey notes that the "high availability of data will require significant enhancements to existing science data system processing and distribution infrastructure." The Earth Science Division's programs and programmatic elements are responding to data challenges by implementing innovative cloud storage

agreements, investing in data and information systems, and developing supercomputing capabilities.

Implementation

NASA's Earth Science Division is organized around four programmatic areas: flight, research, applied sciences, and technology. Together these areas include programs and projects that are responsible for: conducting and sponsoring research to advance scientific understanding of Earth as a system, collecting and disseminating new observations, developing new technologies and computational models, and building the capacity to develop innovative applications of Earth science observations and research results. Flight mission development—from advanced concept studies, to flight hardware development, to on-orbit operation—is managed within the Earth Systematic Missions (ESM) and Earth System Science Pathfinder (ESSP) Programs. ESD conducts research, applied science, and technology efforts through its respective Earth Science Research, Applied Sciences, and Earth Science Technology Programs.

Earth Systematic Missions Program

The ESM Program includes a broad range of multidisciplinary science investigations aimed at developing a scientific understanding of the Earth system and its response to natural and human-induced forces. The ESM Program implements the Earth Science Division's strategic missions, including the foundational missions. The program also includes the systematic missions recommended by the decadal survey and most of the missions providing additional sustained measurements, including land imaging and climate continuity missions.

Earth System Science Pathfinder Program

ESSP implements low- to moderate-cost research and applications missions that foster revolutionary science and train future leaders in space-based Earth science and applications fields. This program includes the new Earth Venture missions recommended in the Earth science decadal survey, which consist of low-cost, PI-led, competed suborbital and orbital missions, as well as instruments for MoOs. The ESSP program also includes operating missions that were competitively selected and Orbiting Carbon Observatory (OCO)-2, which is a follow-on mission to OCO, an ESSP mission that was lost as the result of a launch vehicle failure.

Figure 4.3 NASA Earth Science Missions



Earth Science Research Program

The Earth Science Research Program aims to advance understanding of the components of the Earth system, their interactions, and the consequences of changes in the Earth system for life. These interactions occur on a continuum of spatial and temporal scales; Earth scientists investigate phenomena that range from short-term weather, to long-term climate and motions of the solid Earth and that have local, regional, and global effects. These Earth system components involve multiple, complex, and coupled processes that affect climate, air quality, water resources, biodiversity, and other features that allow our Earth to sustain life and society. A major challenge is to predict changes that will occur on time scales from the next decade to century, both naturally and in response to human activities. To do so requires a comprehensive scientific understanding of the entire Earth system—how its component parts and their interactions have evolved, how they function, and how they may be expected to further evolve on all time scales.

The Earth Science Research Program sponsors research to advance the overarching ESD goals pertaining to Atmospheric Composition, Weather, Carbon Cycle and Ecosystems, Water and Energy Cycle, Climate Variability and Change, and the Earth Surface and Interior.

The research program is also designed to leverage NASA's unique space observation capabilities in relation to research carried out by, and in collaboration with, other federal agencies. For example, NASA participates in many of the interagency subcommittees of the NSTC Committee on Environment, Natural Resources, and Sustainability (CENRS). Similarly, using the observations from ESD flight programs, the research program both advances the interdisciplinary field of Earth system science and provides much of the scientific basis for major periodic assessments of climate change such as the World Meteorological Organization's and United Nations (UN) Environment Programme's quadrennial ozone assessment, the Assessment Reports of the Intergovernmental Panel on Climate Change, and the National Climate Assessment.

The following programmatic elements contribute to a broad range of activities within the Earth Science Research Program. They involve the development of capabilities whose sustained availability is important for the Earth Science Division's future.

Modeling: The Earth Science Research Program approaches modeling from a global Earth system context, with a goal of understanding the Earth as a complete, dynamic system. Model predictions are compared with observations as a means of determining the extent to which we understand the physical processes driving the Earth system. Model predictions are integrated with observations to provide a best estimate of the current state of many Earth system components, using a method known as data assimilation. In addition, models are used to provide short-term forecasts that support field missions, and longer-term forecasts to assess potential responses of the Earth system to various drivers of change. Two large-scale modeling efforts include the Goddard Institute for Space Studies Model E, a global Earth system model designed to address decadal- to centennial-scale problems, and the Goddard Earth Observing System Version 5 (GEOS 5) Earth system model and data assimilation system, which is utilized for shorter time scale problems such as weather forecasting and data assimilation, and short term climate forecasting.

Airborne Science: The airborne science element of the Earth Science Research Program provides access to platforms that can be used for in situ observation and remote sensing of the Earth's atmosphere and surface. NASA maintains a diverse fleet of aircraft, ranging from small propeller planes to unmanned aircraft systems that can remain in the air for more than 24 consecutive hours. These resources are made available to the research community for missions ranging from short, low-altitude flights from the aircraft's home base, to large, multi-aircraft campaigns deployed around the world that can cover long distances for many hours. Airborne platforms may be used to test new measurement approaches, collect detailed in situ and remote-sensing observations to better document and test models of Earth system processes, and provide calibration/validation information for satellites.

Aircraft have proven to be of particular value in Earth system science research for investigation of specific processes.



Known as Operation IceBridge, NASA's annual airborne missions to the Arctic and Antarctica bridge the data gap between the Ice, Cloud, and land Elevation Satellite (ICESat—which ceased operating in 2009) and ICESat-2. Seen from the NASA P-3B on the Apr. 5, 2013 IceBridge survey flight, Helheim Glacier, one of the largest glaciers in Greenland, drains into the ocean through this fjord. *Image Credit: NASA*

They provide the capability to obtain high-resolution temporal and spatial measurements of complex local processes, which can be coupled to global satellite observations for a better understanding of the Earth system. A full listing of aircraft and program details can be found at <https://airbornescience.nasa.gov>.

Surface-Based Measurements: NASA maintains and contributes to a variety of surface-based measurements that provide unique observational capability not otherwise available, as well as calibration/validation/algorithm testing capability for current and future satellite measurements. These networks involve partnerships with agencies, institutions, and scientists all around the world. They address parameters as varied as the concentration of radiatively and chemically active trace gases regulated under the Montreal Protocol on Substances that Deplete the Ozone Layer (UN, 2007); the distribution and properties of atmospheric aerosols that can impact clouds, radiative forcing and human health; and the terrestrial reference frame that is so critical in providing the rigorous information that underlies gravimetric and altimetric measurements that are applied to a broad range of terrestrial and oceanic studies.

Data and Information Systems: NASA's principal Earth science information system is the Earth Observing System

Data and Information System (EOSDIS), which has been operational since August 1994. EOSDIS acquires, processes, archives, and distributes Earth science data and information products created from satellite data, which arrive at the rate of more than five trillion bytes (five terabytes) per day. EOSDIS provides services and tools needed to enable use of NASA's Earth science data in new models, research results, and decision support system benchmarking. EOSDIS also supports the executive branch's Big Earth Data Initiative focusing on interoperability between environmental data systems at NASA, NOAA, and USGS, and has helped pave the way for the USGCRP's Global Change Information System (GCIS).

NASA Earth science information is archived at 12 Distributed Active Archive Centers (DAACs) located across the United States. The DAACs ensure that the data is easily accessible to researchers around the world. Although they specialize by topic area, DAACs also provide services to users whose needs may cross the traditional science discipline boundaries.

The NASA Earth Exchange (NEX) is a new research and collaboration platform for the Earth science community that provides a mechanism for scientific collaboration and knowledge sharing. NEX combines state-of-the-art supercomputing, Earth system modeling, workflow management, NASA remote sensing data, and a knowledge sharing platform to deliver a complete work environment in which users can explore and analyze large datasets, run modeling codes, collaborate on new or existing projects, and quickly share results with Earth science communities.

High-End and Scientific Computing: ESD is responsible for providing high-end computing, networking, and storage capabilities that are critical enablers for Earth system and space sciences. Satellite observations must be converted into scientific data products through retrieval and/or data assimilation processes. Long-term data sets must be synthesized together and become a physically consistent climate-research quality data set through reanalysis. These data products, in turn, provide initial and boundary conditions, validation and verification references, and internal and external constraints to the models that describe the behavior of the Earth system. Two supercomputer systems, with more than 200,000 computer processor cores,

serve the unique needs of all NASA mission directorates including the HEOMD, Aeronautics Research, SMD, and STMD, and NASA-supported PIs at universities. More than 20 petabytes of online disk system and 150 petabytes of tape archive are available for data storage. There is also a small grants program to build the next-generation computational modeling infrastructure, including new computing architecture, data processing and management systems for model-data inter-comparison, and refactoring of computational models.

Applied Sciences Program

As we pursue the answers to fundamental science questions about the Earth system, we realize many important results that can be of near-term use and benefit to society. The overarching purpose of the Applied Sciences Program is to leverage NASA Earth science satellite measurements and new scientific knowledge to provide innovative and practical uses for public and private sector organizations. The program enables near-term uses of Earth science knowledge, discovers and demonstrates new applications, and facilitates adoption of applications by non-NASA stakeholder organizations that have connections to users and decision makers. Specifically, the Applied Sciences Program has three primary goals: enhancing applications research, increasing collaborations, and accelerating applications.

The Applied Sciences Program consists of four application areas (Disasters, Ecological Forecasting, Health and Air Quality, and Water Resources) and the Capacity Building Program (CBP). CBP spans nine societal benefit areas, comprised of the program's four application areas, plus Agriculture, Climate, Energy, Oceans, and Weather. CBP oversees several capacity building efforts including the Applied Remote SENSing Training (ARSET) program, which provides training to access and utilize Earth observing tools and services; DEVELOP, which focuses on workforce development through 10-week applied research project opportunities; the Gulf of Mexico Initiative (GOMI), which focuses on region-specific coastal challenges through partnerships with state and local agencies; and the Regional Visualization and Monitoring System (SERVIR), which is a collaboration with the U.S. Agency for International Development (USAID) and builds capacity to use geospatial information in national decision processes through partnerships with developing countries.



SERVIR-Africa installed wireless sensor networks in Kenya to support the automated frost mapping system they designed and implemented. The near real-time frost mapping system identifies and displays frost-impacted areas by analyzing night time land surface temperature data from NASA's Moderate Resolution Imaging Spectrometers aboard the Terra and Aqua spacecraft, identifying areas with high potential for frost to the Kenya Meteorological Service and agriculture insurance companies. *Image Credit: NASA/SERVIR-Africa*

SERVIR has hubs—active partnerships with regional institutions—in East Africa and the Hindu-Kush Himalayas, with a new hub in South East Asia planned for 2014 and more expansion under consideration. A hub in Central America that operated from 2004–2011 under the auspices of SERVIR now continues to operate independently, still drawing on SERVIR-provided data and tools and garnering support from other international donor agencies. Through SERVIR, the hubs develop national environmental information systems, promote and co-develop cutting-edge applications of satellite data and models with NASA to address environmental challenges, and take advantage of the view from space to assist in the response to dozens of natural disasters.

Together with the Earth Science Research Program, the Applied Sciences Program supports efforts across NASA to use the Agency's expertise in climate observations and models to enhance understanding of climate impacts and inform the nation's ability to anticipate and adapt to a changing climate. One example is the Climate Adaptation Science Investigators (CASI) work group, which investigates climate risks at NASA centers. Additionally, ESD supports researchers at NASA centers and in the broader science community to conduct science that informs USGCRP National Climate Assessments and grows the capacity of the science community to contribute and participate in assessment activities.

The Applied Sciences Program also encourages potential users to envision and anticipate possible applications from upcoming satellite missions and to provide input to mission development teams. For example, the Soil Moisture Active/Passive (SMAP) mission team has created an “early adopters effort” to assist groups who would like to apply their own resources to demonstrate the utility of SMAP data for their particular system or model so that they will be prepared to use the data as soon as possible after the spacecraft is on orbit. Through these types of efforts, the Applied Sciences Program serves as a bridge between the data and knowledge generated by NASA Earth science initiatives and the information and decision-making needs of public and private organizations.

Earth Science Technology Program

The Earth Science Technology Program, operated through the Earth Science Technology Office (ESTO), demonstrates and provides technology research and development projects that advance Earth observing instrumentation, mission components, and information systems to make future missions feasible and affordable. This program is based on a science-driven strategy that employs open peer-reviewed solicitations to produce the best appropriate technologies. ESTO holds a broad portfolio of more than 700 past and active investments at over 100 institutions nationwide. More information about ESTO's program implementation can be found in the Technology Development section below.

Current Missions

To address the challenges involved in recording simultaneous observations of all Earth components and interactions to generate new knowledge about the global integrated Earth system, NASA and its partners developed and launched Earth observing missions and ancillary satellites. As shown in Table 4.4, 17 satellites comprise today's fleet of NASA Earth observing missions.

The scientific benefit of simultaneous Earth observation—the Earth System Science construct—is substantial. NASA's A-Train constellation of satellites is the first Earth science space “super-observatory.” The A-Train consists of five satellites in orbits that cover the same region within 15 minutes, recording near-simultaneous observations of a wide variety of parameters, such as comprehensive measurements of

Table 4.4 Current Earth Science Missions

Mission—Launch Year (Extended or Prime), Partners	Objective
Earth Systematic Missions (ESM) Program	
Tropical Rainfall Measuring Mission (TRMM) —1997 (Extended) in partnership with Japan	First-time use of both active and passive microwave instruments has made TRMM the world's foremost satellite for the study of precipitation and associated storms and climate processes in the tropics.
Landsat-7 —1999 (Extended) in partnership with USGS	Spanning 40 years of multispectral imaging of the Earth's surface, Landsat 7 is part of the long history of land remote sensing spacecraft.
Quick Scatterometer (QuikSCAT) —1999 (Extended)	QuikSCAT's SeaWinds instrument is a specialized microwave radar that measures near-surface wind speed and direction under all weather and cloud conditions over Earth's oceans. Having exceeded its design life by 8 years, QuikSCAT now serves as a transfer standard to calibrate other satellites.
Terra —1999 (Extended) in partnership with Japan and Canada	Studies clouds, water vapor, aerosol particles, trace gases, terrestrial and oceanic surface properties, biological productivity of the land and oceans, Earth's radiant energy balance, the interaction among them, and their effects on climate.
Earth Observing-1 (EO-1) —2000 (Extended)	Advanced land-imaging mission that demonstrates new instruments and spacecraft systems. The hyperspectral instrument (Hyperion) is the first of its kind to provide images of land-surface in more than 220 spectral colors.
Aqua —2002 (Extended) in partnership with Japan and Brazil	Observes the Earth's oceans, atmosphere, land, ice and snow covers, and vegetation, providing high measurement accuracy, spatial detail, and temporal frequency.
Solar Radiation and Climate Experiment (SORCE) —2003 (Extended)	Provides state-of-the-art measurements of incoming X-ray, ultraviolet, visible, near-infrared, and total solar radiation. The measurements specifically address long-term climate change, natural variability and enhanced climate prediction, and atmospheric ozone and UV-B radiation.
Aura —2004 (Extended) in partnership with The Netherlands and the United Kingdom	Studies the chemistry and dynamics of the atmosphere with emphasis on the upper troposphere and lower stratosphere. Provides daily global observations of atmospheric ozone, air quality, and climate parameters.
Ocean Surface Topography Mission/Jason 2 (OSTM/Jason 2) —2008 (Extended) in partnership with EUMETSAT, France, and NOAA	Measures sea surface height by using a radar altimeter mounted on a low-Earth orbiting satellite. Measurements of sea-surface height, or ocean surface topography, reveal the speed and direction of ocean currents and tell scientists how much of the Sun's energy is stored by the ocean.
Suomi National Polar-Orbiting Partnership (NPP) —2011 (Prime) in partnership with NOAA	Serves as the bridge between the EOS satellites and the forthcoming series of Joint Polar Satellite System (JPSS) satellites. Suomi NPP data are being used for climate research and operational weather prediction.

Table 4.4 (Continued) Current Earth Science Missions

Mission—Launch Year (Extended or Prime), Partners	Objective
Earth Systematic Missions (ESM) Program (Continued)	
Landsat Data Continuity Mission (LDCM)/ Landsat 8 —2013 (Prime) in partnership with USGS	Provides moderate-resolution measurements of the Earth's terrestrial and polar regions. Provides continuity with the Landsat land imaging data set. Provides data for land use planning and monitoring on regional to local scales, and supports disaster response and evaluations, and water use monitoring.
Global Precipitation Measurement (GPM) —2014 (Prime) in partnership with Japan	Next-generation observations of precipitation (rain and snow) worldwide every three hours, to advance understanding of the water and energy cycles and extend the use of precipitation data to directly benefit society.
Earth System Science Pathfinder (ESSP) Program	
Gravity Recovery and Climate Experiment (GRACE) —2002 (Extended) in partnership with Germany	Accurately maps variations in the Earth's gravity field. GRACE data is used to estimate global models for the variable Earth gravity field approximately every 30 days, and reveals changes in levels of large underground aquifers.
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) —2006 (Extended) in partnership with France	Combines an active lidar with passive infrared and visible imagers to study the role clouds and aerosols (airborne particles) play in weather, climate and air quality.
CloudSat —2006 (Extended) in partnership with Canada	Provides a comprehensive characterization of the structure and composition of clouds and their effects on climate under all weather conditions using an advanced cloud profiling radar.
Earth Venture Sub-orbital-1 (EVS-1): <ul style="list-style-type: none"> • Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) • Airborne Tropical Tropopause Experiment (ATTREX) • Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) • Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) • Hurricane and Severe Storm Sentinel (HS3) 	Five investigations selected through the first Earth Venture Suborbital opportunity are being conducted from 2010 through 2015.
Aquarius —2011 (Prime) in partnership with Argentina	Measures global sea surface salinity with unprecedented precision. Monthly sea surface salinity maps give clues about changes in freshwater input and output to the ocean associated with precipitation, evaporation, ice melting, and river runoff.

The Earth Systematic Missions (ESM) Program encompasses the division's strategic and directed missions. Table 4.4 includes missions that were selected prior to the creation of the ESM Program Office, such as missions under the previously existing Earth Observing System (EOS) Program. The missions within the Earth System Science Pathfinder (ESSP) Program are competitively selected under the program itself or as Earth Venture missions.



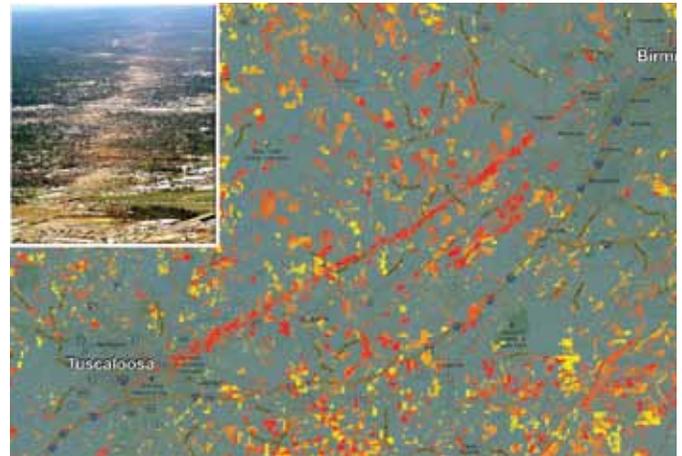
The midnight sun casts a golden glow on an iceberg and its reflection in Disko Bay, Greenland. Much of Greenland's annual ice mass loss occurs through calving of such icebergs. *Image Credit: University of Washington/Ian Joughin*

atmospheric chemistry and composition, including clouds and aerosols, using powerful imaging capabilities. NASA's Aqua, Aura, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and CloudSat satellites, and Japan's Global Change Observation Mission–Water (GCOM-W1, also known as the SHIZUKU) satellite comprise this powerful international constellation. OCO-2 is on the launch manifest to join the configuration in 2014.

The Earth science decadal survey identified five foundational missions to bridge the gap between the aging Earth Observing System and the recommended decadal survey missions to follow. These foundational missions include Glory, Aquarius, Suomi NPP, Landsat Data Continuity Mission (LDCM)/Landsat 8, and Global Precipitation Measurement (GPM). Although Glory was unfortunately lost due to launch vehicle failure, Aquarius, Suomi NPP, and LDCM/Landsat-8 are making critical Earth observation measurements and the recently launched GPM will contribute measurements after it completes on-orbit checkout.

Missions in Formulation and Development

In May 2012, the NRC published the midterm report, *Earth Science and Applications from Space: A Midterm Assess-*



The ravages of deforestation, wildfires, windstorms and insects on global forests during this century are revealed in unprecedented detail in a new study based on data from Landsat-7. The maps from the study are the first to document forest loss and gain using a consistent method around the globe, at high resolution. The forest cover maps also capture natural disturbances such as this 2011 tornado path in Alabama. *Image Credit: NASA/GSFC*

ment of NASA's Implementation of the Decadal Survey (NRC, 2012). NASA's progress towards achievement of the NRC's overall recommendations for Earth observations, missions, technology investments, and priorities for Earth system science received a favorable assessment in this report. The report endorsed the refinements to the NASA Earth science portfolio of planned missions, which include missions and instruments to meet the nation's needs for sustained climate measurements, although it cautioned that the inclusion of initiatives described in NASA's 2010 climate-centric architecture plan could result in an impact on the pace at which the program will be able to conduct the recommended research.

Many of these upcoming missions intend to demonstrate multiple scientific and societal benefits accruing from the synergies that exist between data and observations collected during similar periods of time. In fact, the timing of some missions, like SMAP, has been accelerated. As a result, the SMAP, GPM, and GRACE Follow-on (GRACE FO) missions, and, possibly the Surface Water and Ocean Tomography (SWOT) mission, have the potential to address global and regional water-balance studies together in a manner that could not be achieved by individual investigations.

Table 4.5 identifies Earth science missions that are in formulation or development, with launches planned over the 2014–2020 timeframe. The expected launch years are subject to change, but provide the relative timeframes for development.

Table 4.5 Earth Science Strategic Research Missions in Formulation and Development

Mission—Expected Launch Year, Partners	Objective
Earth Systematic Missions (ESM) Program	
Soil Moisture Active/Passive (SMAP)—NLT 2015*	Soil moisture and freeze-thaw for weather and hydrological cycle processes.
Stratospheric Aerosol and Gas Experiment III (SAGE III-ISS)—NLT 2016*	Global stratospheric aerosols measurements, and measurements of ozone, water vapor and nitrogen dioxide, to understand their significant roles in atmospheric radiative and chemical processes and monitor climate change. SAGE III is scheduled to fly to ISS aboard one of NASA’s commercial Space X flights.
Ice Cloud and land Elevation Satellite-2 (ICESat-2)—LRD under review	Ice sheet height changes for climate change diagnosis and assessment of land carbon standing stock.
Gravity Recovery and Climate Experiment Follow-on (GRACE FO)—NLT 2018* in partnership with Germany	Continue high-resolution gravity field measurements; determine time variable gravity and mass re-distribution involved in Earth system component interactions.
Surface Water and Ocean Topography (SWOT)—2020 in partnership with France and Canada	Oceanography and hydrology through broad swath altimetry. First global determination of the ocean circulation at high resolution and first global inventory of fresh water storage and its change.
Earth System Science Pathfinder (ESSP) Program	
Orbiting Carbon Observatory-2 (OCO-2)—NLT 2015*	Global atmospheric column CO ₂ measurement from space to help quantify CO ₂ fluxes.
Cyclone Global Navigation Satellite System (CYGNSS) Earth Venture Mission-1 (EVM-1)—NLT 2017*	Frequent and accurate measurements of ocean surface winds throughout the life cycle of tropical storms and hurricanes to enable improvement in hurricane forecasting.
Tropospheric Emissions: Monitoring of Pollution (TEMPO) Earth Venture Instrument-1 (EVI-1)—available in 2018 for flight as a hosted payload	TEMPO’s measurements from geostationary orbit (GEO) of tropospheric ozone, ozone precursors, aerosols, and clouds will create a revolutionary dataset (hourly and at high spatial resolution) that provides understanding and improves prediction of air quality and climate forcing.

* Reflects the Agency baseline commitment to launch NLT the year identified.



TOP LEFT: This artist's concept depicts NASA's OCO-2 spacecraft. *Image Credit: NASA/JPL*

BOTTOM LEFT: NASA's OCO-2 spacecraft is moved into a thermal vacuum chamber at Orbital Sciences Corporation's Satellite Manufacturing Facility in Gilbert, Ariz., for a series of environmental tests. The tests confirmed the integrity of the observatory's electrical connections and subjected the OCO-2 instrument and spacecraft to the extreme hot, cold and airless environment they will encounter once in orbit. *Image Credit: NASA/JPL*

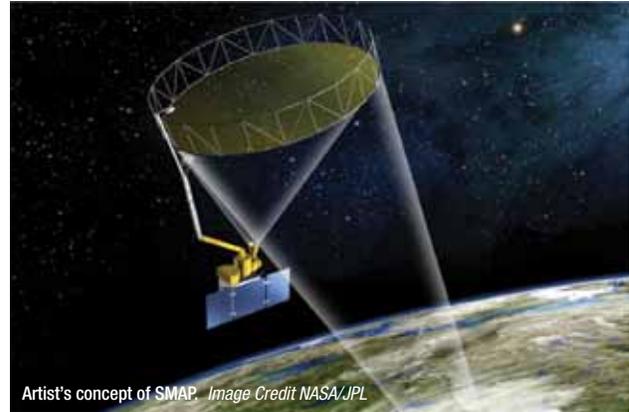


TOP RIGHT: The SMAP spacecraft and instrument, having just been put together into what is called the "Observatory" in January 2014. The spinning portion of SMAP's instrument system is seen mounted on top of the rectangular, box-like structure of the spacecraft. Prominently featured in the upper portion of the instrument and on its right-hand side are the deployable reflector antenna, which looks like a bundle of black-colored tubular elements, and the deployable boom above (also black in color), which will eventually support the antenna while spinning in space. *Image Credit: NASA/JPL*

SMAP: Understanding the Earth System through Interdisciplinary Synergies

NASA's SMAP mission will provide global measurements of soil moisture and the soil freeze/thaw state. The NRC Earth science decadal survey explains how SMAP will enable interdisciplinary studies of the Earth system:

Soil moisture serves as the memory at the land surface in the same way as sea-surface temperature does at the ocean surface. The use of sea-surface temperature observations to initialize and constrain coupled ocean-atmosphere models has led to important advances in long-range weather and seasonal prediction. In the same way, high-resolution soil-moisture mapping will have transformative effects on Earth system science and applications (Entekhabi et al., 1999; Leese et al., 2001). As the ocean and atmosphere community synergies have led to substantial advances in Earth system understanding and improved prediction services, the availability of high-resolution mapping of surface soil moisture will be the link between the hydrology and atmospheric communities that share interest in the land interface. The availability of



such observations will enable the emergence of a new generation of hydrologic models for applications in Earth system understanding and operational severe-weather and flood forecasting.

Future Missions

Table 4.6 identifies the Earth science missions that are in the pre-formulation phase, with planned launches beginning in 2020. The future missions under study include decadal

survey missions, sustained climate and land imaging measurement missions, and Earth Venture missions, instruments, and sub-orbital investigations.

Table 4.6 Future Earth Science Strategic Research Missions

Mission—Expected Launch Year, Partners	Objective
Earth Systematic Missions (ESM) Program	
Sustained Solar irradiance measurements—Instrument of opportunity—No earlier than (NET) 2020	Responsibility transferred from NOAA to NASA in the FY2014 President's budget request to provide sustained solar irradiance measurements beginning in the 2020 timeframe. Will continue the 34 year measurement record that includes SORCE and the Total solar irradiance Calibration Transfer Experiment (TCTE).
Pre-Aerosol, Cloud, ocean Ecosystem (PACE)—NET 2020	Provide aerosol, cloud, and ocean color measurements until availability of decadal survey Tier 2 Aerosol-Clouds-Ecosystems mission.
NASA-India Space Research Organization Synthetic Aperture Radar (NI-SAR)—NET 2021 in partnership with India	NI-SAR (a.k.a. DESDynI Radar) mission to study solid Earth deformation (earthquakes, volcanoes, landslides), changes in ice (glaciers, sea ice) and changes in vegetation.

Table 4.6 (Continued) Future Earth Science Strategic Research Missions

Mission—Expected Launch Year, Partners	Objective
Earth Systematic Missions (ESM) Program (Continued)	
Earth’s Radiation Budget—on JPSS-2—NET 2021	Responsibility transferred from NOAA to NASA in the FY2014 President’s Budget Request to provide sustained measurements of the Earth’s radiation budget that have been made by the Clouds and the Earth’s Radiant System (CERES) instruments on TRMM, Terra, Aqua and Suomi NPP and are planned for the JPSS-1 in 2016. The Radiation Budget Instrument (RBI) to be provided by NASA for flight on JPSS-2 in 2021 will be a follow-on to the CERES instruments.
Future Land Imaging—Under study	To extend global Landsat-quality multispectral and thermal infrared measurements beyond the expected operation of Landsat-8, NASA initiated, in FY 2014, the Sustainable Land Imaging Architecture Study, with support from USGS. The study will define the scope, measurement approaches, cost, and risk of a viable long-term land imaging system that will achieve national objectives. Evaluations and design activities will include consideration of a range of solutions including large and small dedicated spacecraft, formation flying, hosted instruments, integration of other compatible land imaging data sets, and international and private sector collaborations.
Climate Absolute Radiance and Refractivity Observatory (CLARREO)—NET 2023	CLARREO will make highly accurate spectrally resolved measurements of reflected solar and thermally emitted radiation that are directly traceable to International System of Units (SI) standards to achieve the required levels of accuracy for quantification and characterization of the Earth’s energy balance as an indicator of climate change on decadal scales.
Tier 2 and 3 Missions—TBD	<ul style="list-style-type: none"> • Active Sensing of CO2 Emissions Over Nights, Days, and Seasons (ASCENDS) • Geostationary Coastal and Air Pollution Events (GEO-CAPE) • Hyperspectral Infrared Imager (HyspIRI) • Aerosol-Clouds-Ecosystems • Precipitation and All-weather Temperature and Humidity (PATH) • Snow and Cold Land Processes (SCLP) • Global Atmospheric Composition Mission (GACM) • Three-Dimensional Tropospheric Winds (3D-Winds) (demo) • Lidar Surface Topography (LIST) • Gravity Recovery and Climate Experiment-II (GRACE-II)
Earth System Science Pathfinder (ESSP) Program	
Future Earth Venture Solicitations	<ul style="list-style-type: none"> • Earth Venture Suborbital (EVS)—2 in 2013 and at 4-year intervals • Earth Venture Instrument (EVI)—2 in 2013 and at 18-month intervals • Earth Venture Full Orbital Missions(EVM)—2 in 2015 and at 4-year intervals

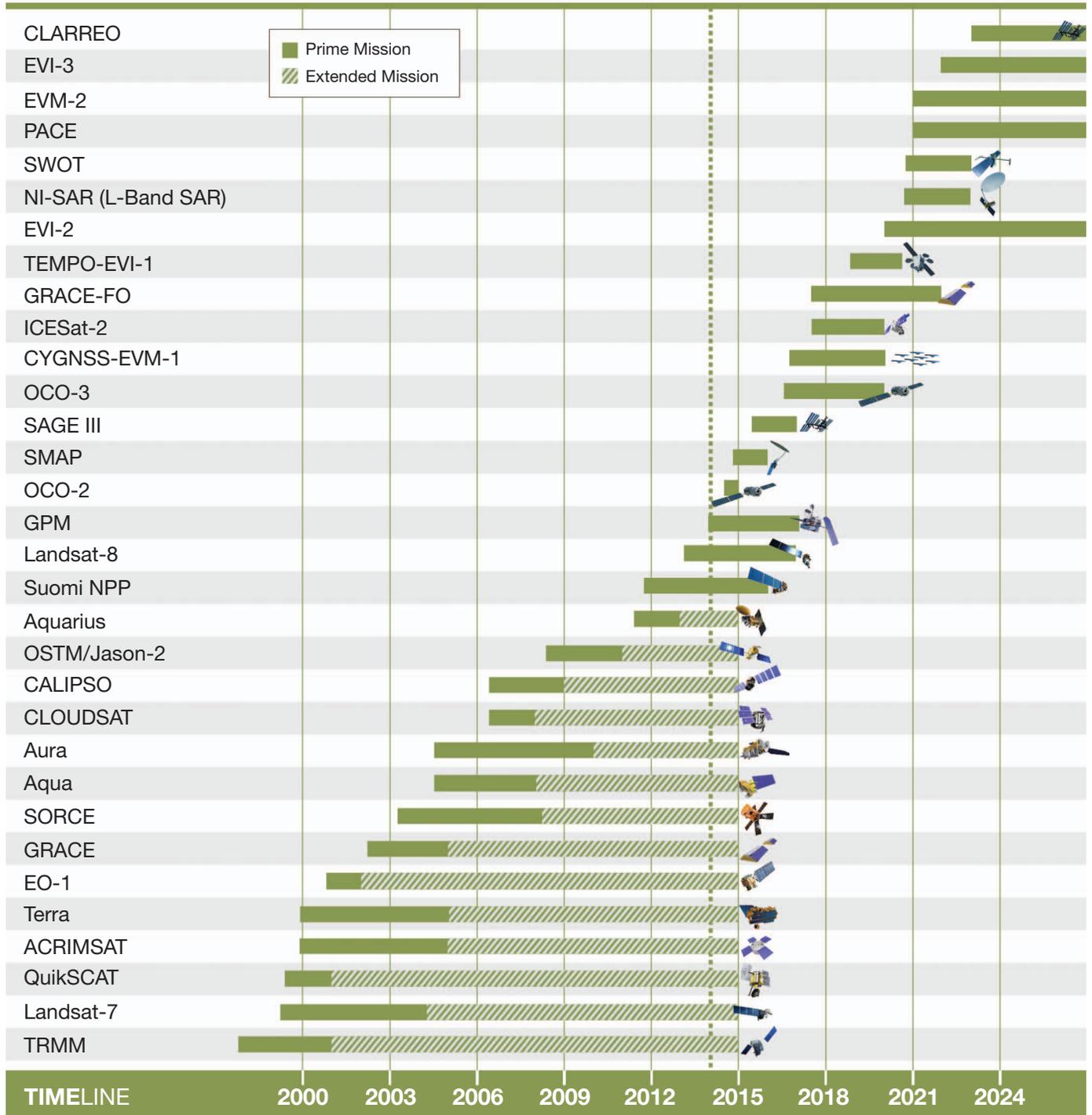
Technology Development

The Earth Science Technology Office (ESTO) is the lead technology office for the Earth Science Technology Program. The primary science requirements for ESTO technologies are derived from the Earth science decadal survey. In general, the second and third tier Earth science decadal survey

missions involve inherent technological challenges. A number of the recommended instruments will contain active components such as radars and/or lasers. Other second and third tier missions will require larger collection optics and antennas to meet requirements. Therefore, ESTO is principally focused on advancing technologies needed for the second and third tier missions and measurements. The

Figure 4.4 Summary of Earth Science Missions

Earth Science Timeline



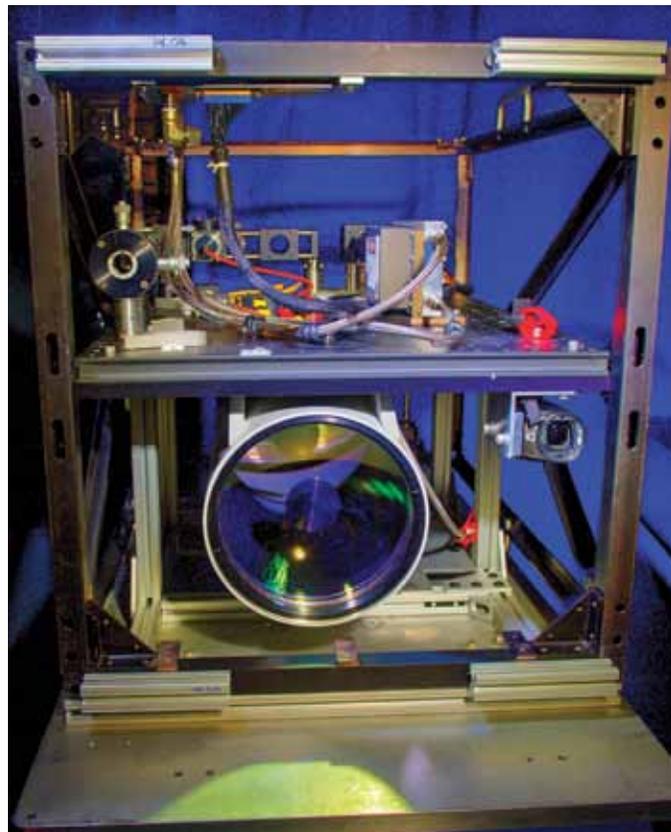
The extended missions depicted in Figure 4.4 are approved for continued operations based on a senior peer review conducted by scientists every two years to determine the scientific value and priority of further mission extensions.

Earth Science Technology Program consists of the following four elements.

Advanced Technology Initiatives (ATI): The ATI element conducts technology concept studies that help establish the range of technical capability requirements that the technology program must address, and identify the pros and cons of available technology implementation options. The ATI element also includes the Advanced Component Technology (ACT) sub-element. ACT leads research, development, testing, and demonstration of component- and subsystem-level technologies for use in state-of-the-art Earth science instruments and information systems. ACT is primarily geared toward producing technologies that reduce the risk, cost, size, mass, and development time of future space-borne and airborne missions.

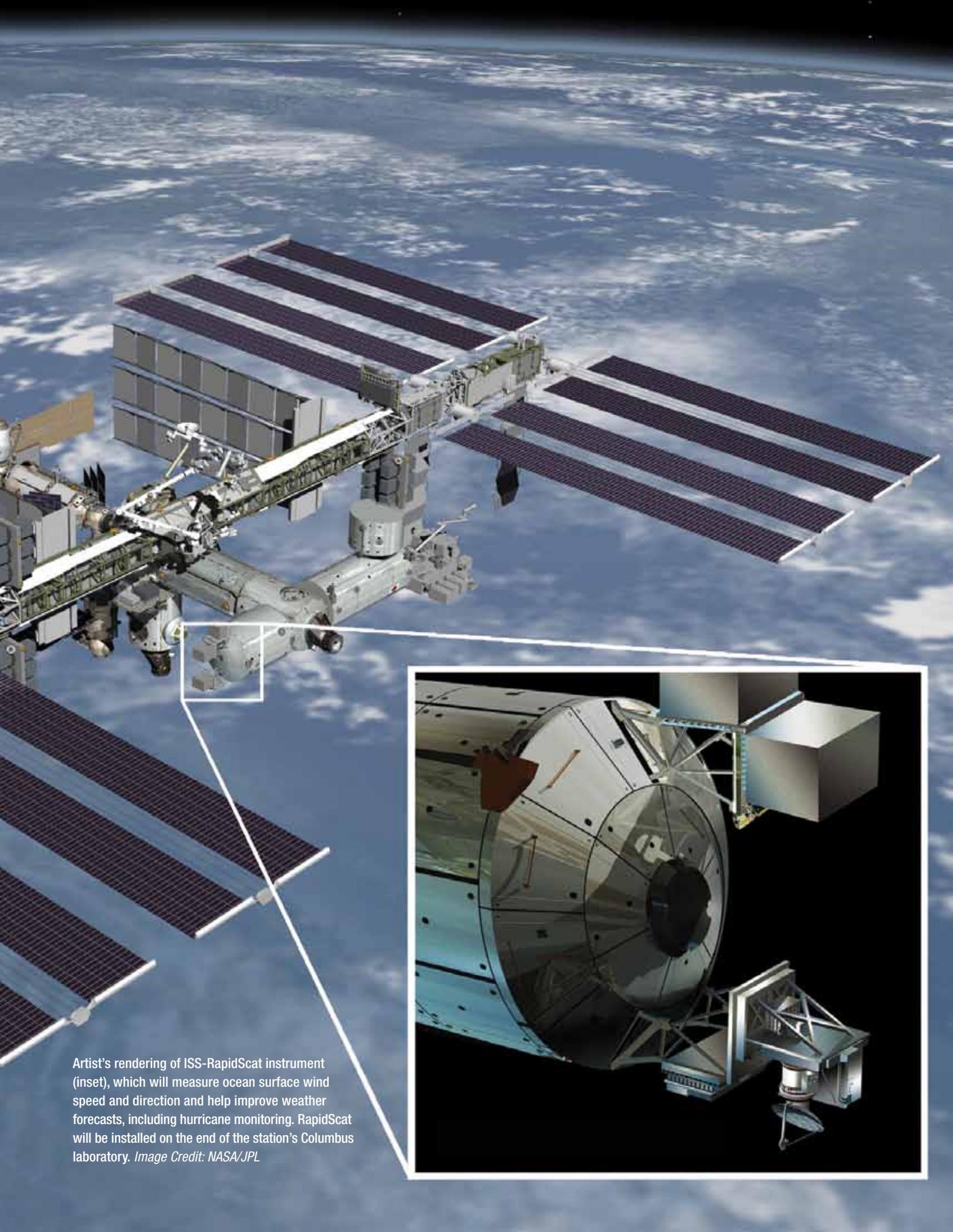
Instrument Incubator Program (IIP): The IIP element provides funding to support new instrument and observation techniques, from concept development through breadboard and flight demonstrations. Instrument technology development of this scale outside a flight project consistently leads to smaller, less resource-intensive flight instruments. Developing and validating these technologies before their use in science missions and campaigns improves their acceptance, enables infusion, and significantly reduces costs and schedule uncertainties.

Advanced Information Systems Technologies (AIST): Advanced information systems play a critical role in the collection, handling, and management of large amounts of Earth science data, in space and on the ground. Advanced computing and transmission concepts that permit the dissemination and management of terabytes of data are essential to NASA's vision of a unified observational network. The AIST element develops and demonstrates information system technologies to facilitate the communication, processing, and management of remotely sensed data, as well as the efficient generation of data products and models. AIST employs an end-to-end approach to evolve these critical technologies from the space segment, where the information pipeline begins, to the end user, where knowledge is advanced.



Funded by the Earth Science and Technology Office and Goddard Internal Research and Development Program, the airborne Lidar Surface Topography (LIST) Simulator is proving the technology needed to measure the height of Earth's surface to within 10 centimeters and at 5 meter resolution. *Image Credit: NASA/GSFC*

In-Space Validation of Earth Science Technologies (InVEST): Since 1998, NASA's Earth Science Division has sought to facilitate space demonstrations of key technology projects through partnerships, such as the NASA CSLI, and follow-on projects, particularly under other NASA programs such as ESSP. In 2012, NASA established InVEST as a nimble, competitive Earth Science Technology Program element to retire risk and space-validate technologies. The first InVEST solicitation, which sought small instruments and instrument subsystems relevant to Earth science measurements, targeted the CubeSat platform. Four (of 24) proposals were selected in April 2013 that included a polarimeter, a radiometer, a photon-counting laser detector, and a carbon nanotube-based bolometer.



Artist's rendering of ISS-RapidScat instrument (inset), which will measure ocean surface wind speed and direction and help improve weather forecasts, including hurricane monitoring. RapidScat will be installed on the end of the station's Columbus laboratory. *Image Credit: NASA/JPL*

Earth and Space Science from the **International Space Station**

SMD works in close partnership with the ISS Program to enable science observations from the ISS. The ISS provides the access to space and most on-orbit resources (power, data and communications, instrument operations, and post-flight disposal). In some cases, ISS provides some or all of the initial hardware, while for others, SMD develops and delivers the hardware. In all cases SMD defines the science observations and funds the processing of the data into scientific observations and research results.

For Earth observations, the ISS provides a specific and unique perspective. Its mid-inclination orbit at +/- 51 degrees enables visibility of most of the population centers on the Earth, of all the tropical regions, and of many critical dynamic phenomena. The low altitude enables high-resolution observations, while the precessing orbit allows the ISS-mounted instruments to cross orbits with the extensive fleet of polar and geosynchronous Earth observing satellites, allowing ISS instruments to be cross checked and cross calibrated with those other observations. This capability is particularly important to develop and improve long-term data records that require consistency across generations of observing instruments in highly varying orbits.

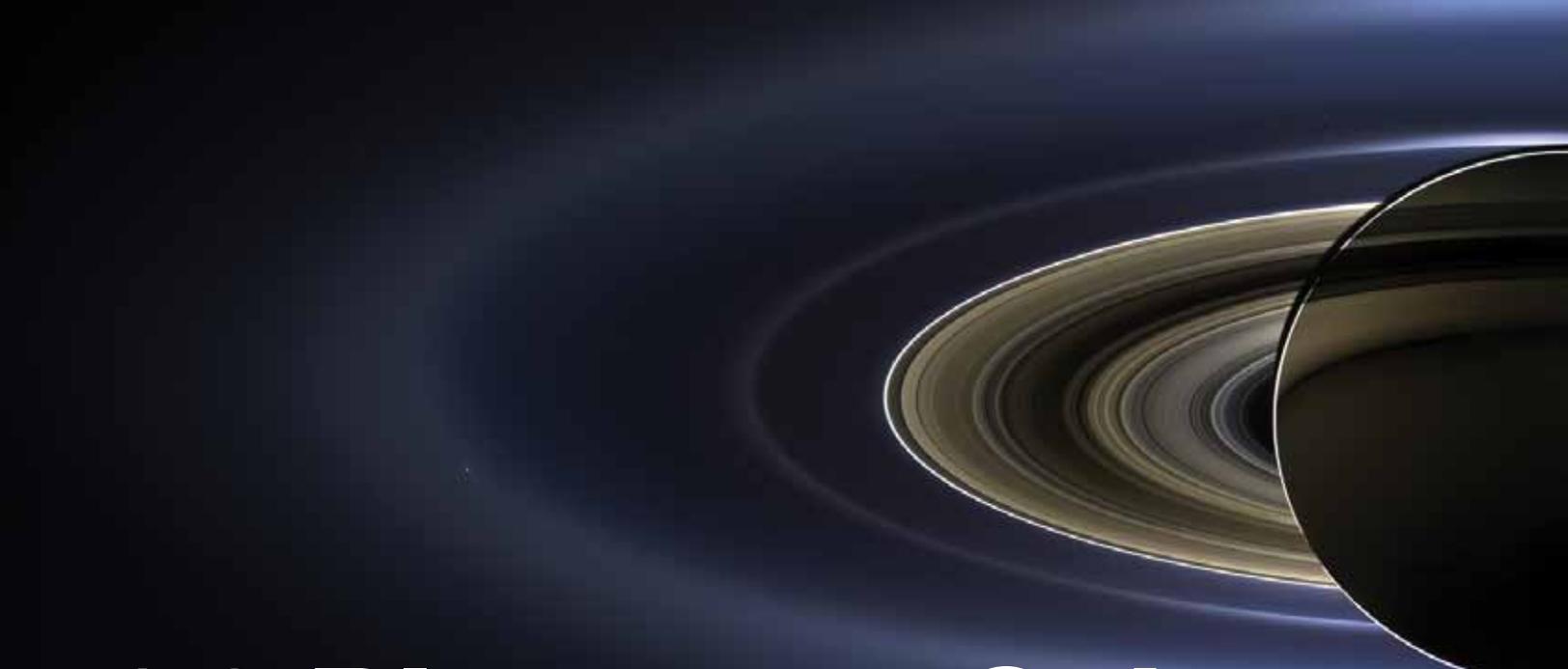
The ISS is useful for astrophysics research because it offers a large, stable platform that can support experiments with large mass, large power requirements, high data rates, and modest pointing requirements, which would be difficult or impossible to support on a satellite bus. The ISS platform is most useful for particle astrophysics and high energy astrophysics.

NASA will be making use of these capabilities for a number of Earth and space observations. The Hyperspectral Imager for the Coastal Ocean (HICO) is operating now on ISS, making measurements of coastal and ocean color. The ISS SERVIR Environmental Research and

Visualization System (ISERV) is providing useful images for use in disaster monitoring and assessment and environmental decision making. Future instruments on ISS include the Rapid Scatterometer (RapidScat) instrument to continue ocean winds measurements, the Cloud-Aerosol Transport System (CATS) to make lidar aerosol measurements, the Lightning Imaging Sensor (LIS) that will measure global lightning (amount, rate, radiant energy) during both day and night, and the Stratospheric Aerosol and Gas Experiment III (SAGE III) instrument to measure atmospheric ozone profiles, extending a 20+ year data record for NASA. In particular, the inclined orbit of ISS is well suited for obtaining latitudinal distributions of ozone-destroying gases using SAGE III's primary solar occultation viewing mode.

For astrophysicists, the Cosmic Ray Energetics and Mass (CREAM) experiment will extend direct measurements of cosmic rays to energies capable of generating gigantic air showers, which have mainly been observed with ground-based experiments with no elemental identification. The Neutron star Interior Composition Explorer (NICER) mission will explore the exotic states of matter inside neutron stars, where density and pressure are higher than in atomic nuclei, confronting theory with unique observational constraints.

Looking to the future, NASA plans welcome proposals for instruments or even small missions that are best adapted to the ISS. The Earth Venture Mission (EVM) and Earth Venture Instrument (EVI) solicitations are released regularly and are open to all platforms, including the ISS. Similarly, the Astrophysics and Heliophysics Explorer AOs allow for ISS-based Mission of Opportunity proposals. The ISS Program has been working with the SMD to improve the utility and usability of the ISS as a science observation platform, which should support more substantial Earth and space observations from the ISS.



4.3 Planetary Science

Strategy

Planetary science is a grand human enterprise that seeks to understand the history of our solar system and the distribution of life within it. The scientific foundation for this enterprise is described in the NRC planetary science decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022* (NRC, 2011). Planetary science missions inform us about our neighborhood and our own origin and evolution; they are necessary precursors to the expansion of humanity beyond Earth. Through five decades of planetary exploration, NASA has developed the capacity to explore all of the objects in our solar system. Future missions will bring back samples from some of these destinations, allowing iterative detailed study and analysis back on Earth. In the future, humans will return to the Moon, go to asteroids, Mars, and ultimately other solar system bodies to explore them, but only after they have been explored and understood using robotic missions.

NASA's planetary science program pursues a strategy of surveying the planetary bodies of our solar system and targeting repeated visits to those bodies likely to enable

greatest progress toward answering fundamental science questions. For selected planetary bodies, science drivers require successive visits that progress from fly-by missions, to orbiters, to landers and entry probes, to rovers, and, ultimately, to sample return missions. With the imminent fly-by of the dwarf planet Pluto by the New Horizons mission in 2015, NASA will have made significant progress towards an initial reconnaissance of all the major bodies in the solar system within 33 Astronomical Units (AU) of the Sun. In addition, with the arrival of the Dawn spacecraft at the dwarf planet Ceres; the completion of the Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) mission at Mercury; and continuing robotic exploration of Mars; NASA has built on previous reconnaissance efforts with more in-depth studies of nearby targets. Missions in development and those planned for the future continue the journey.

NASA's strategic objective in planetary science is to **ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere**. We pursue



SATURN ECLIPSE

Saturn eclipsing the Sun, seen from behind from the Cassini orbiter. The image is a composite assembled from images taken by the Cassini spacecraft on September 15, 2006.

Image Credit: NASA/JPL

this goal by seeking answers to fundamental science questions that guide NASA's exploration of the solar system:

- How did our solar system form and evolve?
- Is there life beyond Earth?
- What are the hazards to life on Earth?

The Planetary Science Division has translated these important questions into science goals that guide the focus of the division's science and research activities:

- Explore and observe the objects in the solar system to understand how they formed and evolve
- Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve
- Explore and find locations where life could have existed or could exist today.
- Improve our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere

- Identify and characterize objects in the solar system that pose threats to Earth, or offer resources for human exploration

In selecting new missions for development, NASA's Planetary Science Division strives for balance across mission destinations, using different mission types and sizes. Achievement of steady scientific progress requires a steady cadence of missions to multiple locations, coupled with a program that allows for a consistent progression of mission types and capabilities, from small and focused, to large and complex, as our investigations progress. The division also pursues partnerships with international partners to increase mission capabilities and cadence and to accomplish like-minded objectives.

Challenges

Many of the key challenges the Planetary Science Division faces in carrying out the NASA *2014 Science Plan* are common across all of the SMD science divisions, and are well articulated in chapter 3.3 (e.g., access to space,

mission cost estimation and management, technology development and demonstration, and impediments to international collaboration).

The budget environment assumed by the decadal survey has not been realized, impacting the Planetary Science Division's ability to implement all the decadal survey recommendations within the decade. In a constrained budget environment, NASA may need to make tradeoffs between competed and strategic missions, across planetary destinations, and among research and technology investments—all while supporting the most meritorious science and technology investigations proposed, as well as providing opportunities to develop the workforce, especially early-career scientists.

In addition, NASA faces concerns regarding the availability of Plutonium 238 (Pu-238), which fuels the Radioisotope Power Systems (RPS) that provide electrical power for spacecraft and planetary probes where the Sun is too far distant, not consistently observable, or too obscured to rely on solar energy. U.S. production of Pu-238 ceased in the 1980s and the limited, existing supply has continued to age. Because availability of Pu-238 is so important to planetary science, and ultimately to human exploration, the Planetary Science Division was assigned the responsibility for funding the infrastructure required to produce a reliable supply of Pu-238 and RPS. The Planetary Science Division is working with DOE to restart domestic production of Pu-238 under a reimbursable agreement. This effort will ensure an RPS capability is maintained to allow planetary missions throughout the solar system for decades to come.

Finally, much of the Planetary Science Division's technology development has come from investments made in implementing the larger strategic missions, such as Cassini, Mars Reconnaissance Orbiter (MRO), and Mars Science Laboratory (MSL). With fewer potential strategic missions planned for the future, investments in technology are also being reduced to support existing commitments to missions in development and those currently operating.

Implementation

The Planetary Science Division includes programs with three major classes of mission destinations:

- **Inner planets:** Earth's Moon, Mars and its satellites, Venus, and Mercury
- **Outer planets:** Jupiter and its rings and moons, especially Europa; Saturn and its rings and moons, especially Titan and Enceladus; Uranus and its moons; Neptune and its moon Triton; the dwarf planet Pluto and its small moons; and other Kuiper Belt Objects
- **Small bodies:** Comets, asteroids, and the dwarf planet Ceres in the asteroid belt

The division manages missions to these destinations (including any associated research) through three mission development programs, and two research programs.

Discovery Program

This program is designed to develop a series of small, PI-led, innovative planetary missions on a frequent basis, solicited from the community as complete scientific investigations through an open, competitive AO. Since the Discovery Program was created in 1992, 11 missions have been selected, and 10 have completed development and launched.

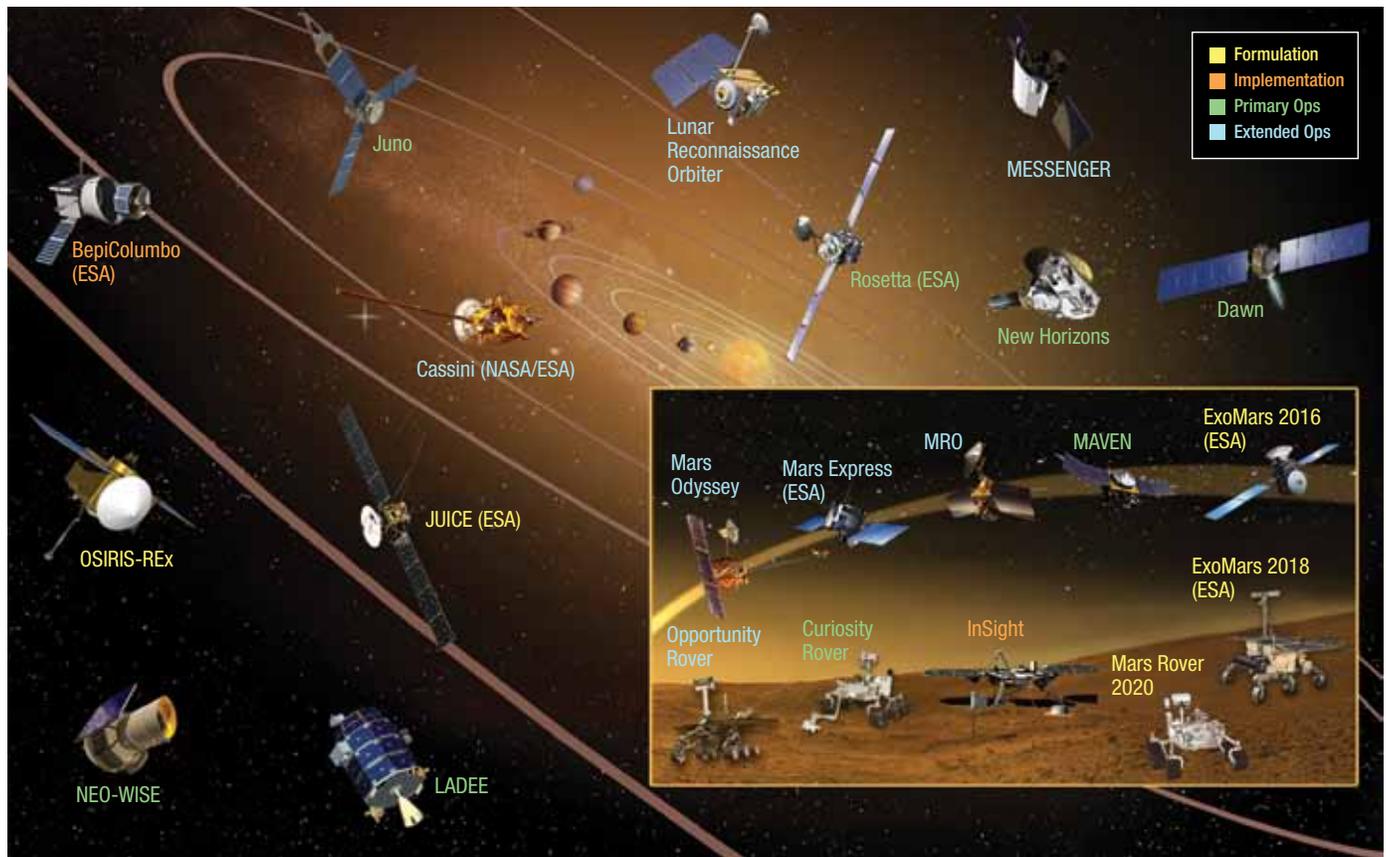
New Frontiers Program

This program is designed to develop a series of medium, PI-led, cost-capped, competed planetary missions solicited from the community as complete scientific investigations through an open AO. New Frontiers missions differ from Discovery missions due to a larger cost cap size, and the restriction that proposed missions are limited to a list provided in the AO. In the past this mission list has been recommended by the NRC's planetary science decadal survey. New Frontiers has selected three missions, and two have completed development and launched. New Frontiers may also develop instruments for international MoOs.

Mars Exploration Program

The Mars Exploration Program (MEP) is a science-driven, technology-enabled effort to characterize and understand Mars as a system, including its current environment, climate and geological history, and biological potential. In a strategy generally known as "Follow the Water," measurements were carried out using robotic assets at Mars

Figure 4.5 NASA Planetary Science Missions



over the past decade. With mounting evidence of a wet and warm past on Mars, the program’s focus is shifting to answering the next logical question, “Did life ever arise on Mars?” The successes of recent missions have led NASA to conclude that Mars could have supported microbial life. Therefore, the program is evolving to focus on determining whether Mars was ever habitable and, through a strategy of “Seeking Signs of Life,” if evidence of extinct or extant life can be identified. Although constrained budgets do not support a sample return mission in the foreseeable future, the eventual collection and return of samples from Mars remains the highest strategic priority in the decadal survey. MEP is a loosely coupled program, meaning new mission objectives are built on discoveries arising from past and present objectives. MEP also maintains a data relay network of Ultra-High Frequency (UHF) radios on all orbiters that NASA sends to the Red Planet to enable communication with future NASA and international partner landers and rovers. Currently, all rover data is relayed via the two NASA science orbiters at Mars—MRO and Mars Odyssey.

Planetary Science Research and Analysis Program

Completed research and analysis enables utilization of the data returned by planetary science missions. Discoveries and concepts generated by the Planetary Science Research and Analysis (R&A) Program are the genesis of scientific priorities, new mission concepts, and science instruments, and provide the crucial context within which mission data are interpreted. Planetary science is inherently crosscutting, spanning ground-based telescope observations, theoretical work, laboratory studies, fieldwork, and the continuing analysis and modeling of data and returned samples from past missions. New, emergent fields of research sometimes lead to new research program elements such as the interdivisional, exoplanets program coordinated between the Planetary Science and Astrophysics Divisions (highlighted on page 87).

The division has recently reorganized its planetary science instrument development into two new projects—MatISSE

(Maturation of Instruments for Solar System Exploration) and PICASSO (Planetary Instrument Concepts for the Advancements of Solar System Observations)—which address low-TRL (TRL 1-3) and mid-TRL (TRL 3-6) technologies, and are further discussed in the Technology Development section.

The Planetary Science Research and Analysis Program provides unique mission support capabilities to enable and facilitate planetary science research:

- Sample return curation facilities to store, disseminate, and support the analysis of extraterrestrial samples, including those returned from other planetary bodies
- The Planetary Data System (PDS) to archive and disseminate data from planetary science missions
- Virtual institutes such as the NASA Astrobiology Institute (NAI) and the new Solar System Exploration Research Virtual Institute (SSERVI) to enable broad collaboration on key scientific foci

Near-Earth Objects Program

NEOs are comets and asteroids that have been nudged by collisions and the gravitational influence of nearby planets into orbits that allow them to enter the Earth's neighborhood. NASA leads the world in the detection and characterization of NEOs and provides critical funding to support the ground-based observatories that are responsible for the discovery of NEOs. In particular, the NEO Program has catalogued more than 95% of all NEOs over one-kilometer in size and enabled flight missions to study asteroids and comets. The Planetary Science Division funds research activities to better understand the motions, compositions and nature of these objects, including the use of optical and radar techniques to better understand their orbits, shapes, sizes and rotation states. Asteroids are not only important when they cross the Earth's orbit; studying asteroids can provide insights into the origins of the solar system.

The NEO Program provides unique mission support capabilities to enable and facilitate this research:

- The Minor Planet Center at the Smithsonian Astrophysical Observatory to catalog all asteroids, comets, Kuiper Belt objects, and other small bodies and all known NEOs in our solar system

- Nationally unique facilities that complement robotic space explorers, including the Infrared Telescope Facility in Hawaii, the Goldstone Solar System Radar, and SMD's partnership with NSF in the operation of the Arecibo planetary radar

Current Missions

The Planetary Science Division currently has ten satellites in orbit, two rovers on Mars, and is participating in five international missions. Table 4.7 highlights the current planetary science missions.

Current missions to inner planets include the Discovery missions: Dawn, which has completed its survey of the asteroid Vesta and is on its way to survey the dwarf planet Ceres; and MESSENGER, which is in its final year of surveying Mercury. Two missions are currently orbiting the Moon: Lunar Atmosphere and Dust Environment Explorer (LADEE) was launched in September 2013, for a four-month mission to investigate the tenuous atmosphere of the Moon and the dust lofted into the lunar atmosphere; and Lunar Reconnaissance Orbiter (LRO) is in its 5th year orbiting the Moon, investigating volatiles in the polar regions, the early processes that formed the Moon, the impact history recorded by the Moon, and the Moon's interaction with the solar wind and space environment.

Additionally, the Mars Exploration Program has two missions orbiting Mars (Mars Odyssey and MRO) and two rovers on the Martian surface. Opportunity continues to rove and conduct science investigations, and Curiosity continues to make new discoveries with its suite of advanced tools and analytical instruments. MAVEN, which launched in 2013, will explore Mars's upper atmosphere, ionosphere, and interactions with the Sun and solar wind to determine the role that loss of volatile compounds—such as carbon dioxide, nitrogen dioxide, and water—from Mars's atmosphere to space has played through time. This research will provide insight into the history of the planet's atmosphere, climate, liquid water, and habitability. NASA also participates in the payloads and scientific investigations of the current ESA Mars Express orbiter, as well as the ESA Venus Express orbiter, and the JAXA Venus Climate Orbiter.



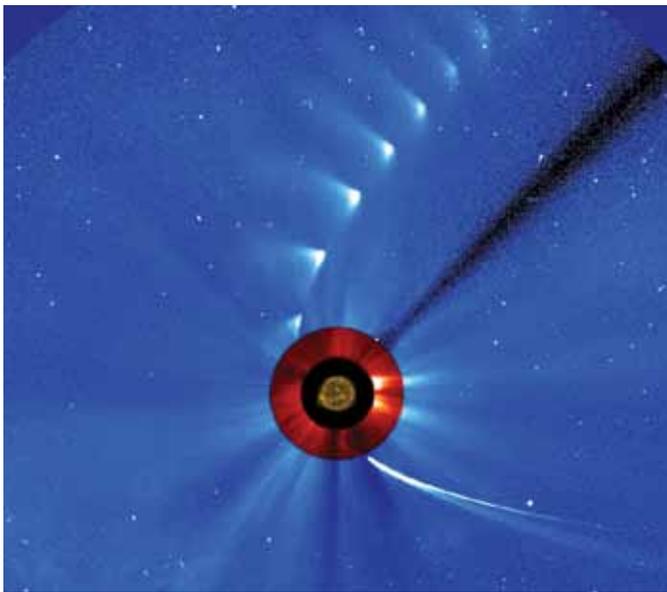
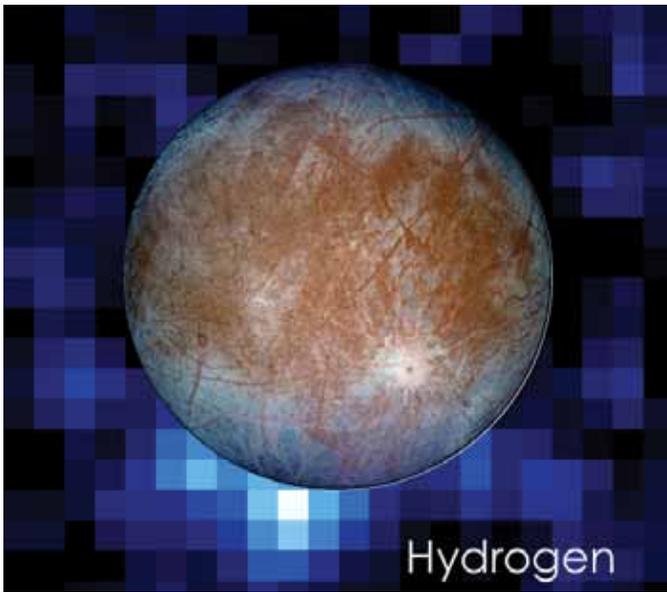
This set of images compares the Link outcrop of rocks on Mars with similar rocks seen on Earth. The image of Link, obtained by NASA's Curiosity rover, shows rounded gravel fragments, or clasts, up to a couple inches (few centimeters) in size, within the rock outcrop. Erosion of the outcrop results in gravel clasts that fall onto the ground, creating the gravel pile at left. The Link outcrop's characteristics are consistent with a sedimentary conglomerate, or a rock that was formed by the deposition of water and is composed of many smaller rounded rocks cemented together. A typical Earth example of sedimentary conglomerate formed of gravel fragments in a stream is shown on the right. *Image Credit: NASA/JPL*

Table 4.7 Current Planetary Science Missions

Mission—Expected Launch Year, Partners	Objective
Discovery Program	
Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) —2004 (Extended)	Image all of Mercury for the first time, as well as gather data on the composition and structure of Mercury's crust, its geologic history, the nature of its active magnetosphere and thin atmosphere, and the makeup of its core and the materials near its poles.
Venus Express —2005 (Extended) ESA mission with U.S. participation	Investigating the noxious atmosphere and clouds in detail and making global maps of the planet's surface temperatures..
Dawn —2007 (Prime)	Characterizing the conditions and processes of the solar system's earliest epoch by investigating in detail the dwarf-planets (Ceres and Vesta), which have remained intact since their formation.
Lunar Reconnaissance Orbiter (LRO) —2009 (Extended) in partnership with HEOMD	Identify lunar sites that are close to potential resources and have high scientific value, favorable terrain, and the environment necessary for safe future robotic and human lunar missions.
Venus Climate Orbiter —2010 (Prime) JAXA mission with U.S. participation	Study the dynamics of the atmosphere of Venus from orbit, particularly the upper atmosphere super-rotation and the three-dimensional motion in the lower part of the atmosphere, using multi-wavelength imaging. Measure atmospheric temperatures and look for evidence of volcanic activity and lightning.

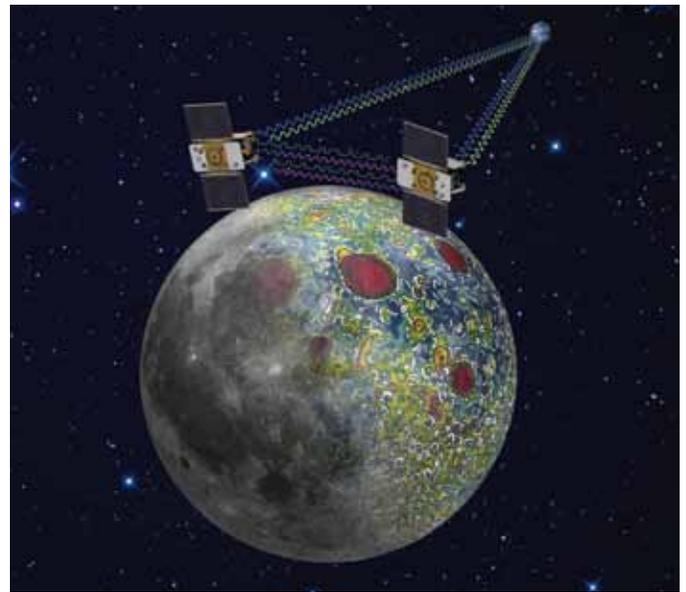
Table 4.7 (Continued) Current Planetary Science Missions

Mission—Expected Launch Year, Partners	Objective
New Frontiers Program	
New Horizons —2006 (Prime)	Make the first reconnaissance of Pluto, Charon, and one or more Kuiper Belt objectives to reveal the origin and evolution of our planetary neighbors.
Juno —2011 (Prime)	Improve our understanding of our solar system’s beginnings by revealing the origin and evolution of Jupiter. Will also look deep into Jupiter’s atmosphere to measure composition, temperature, cloud motions and other properties.
Mars Exploration Program	
Mars Odyssey —2001 (Extended)	Globally map the amount and distribution of many chemical elements and minerals that make up the Martian surface. Maps of hydrogen distribution led scientists to discover vast amounts of water ice in the polar regions buried just beneath the surface.
Mars Express —2003 (Extended) ESA mission with U.S. participation	Answer fundamental questions about the geology, atmosphere, surface environment, history of water and potential for life on Mars.
Opportunity (Mars Exploration Rover) —2003 (Extended) in partnership with Germany	Perform on-site geological investigations on Mars to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars. Now in the seventh year of a 90-day mission, Opportunity is poised to explore the giant crater Endeavor.
Mars Reconnaissance Orbiter (MRO) —2005 (Extended) in partnership with Italy	Provide information about the surface, subsurface, and atmosphere of Mars. Characterizes potential landing sites for other missions including MSL. Detected evidence that water persisted on the surface of Mars for a long period of time, and is examining underground Martian ice.
Mars Science Laboratory (MSL)/Curiosity rover —2011 (Prime) in partnership with Canada, France, Germany, Spain and Russia	Assess whether Mars ever was, or is still today, an environment able to support microbial life. MSL’s mission is to determine the planet’s “habitability.”
Mars Atmosphere and Volatile Evolution (MAVEN) —2013 (Prime) in partnership with France	Explore Mars’s upper atmosphere, ionosphere and interactions with the Sun and solar wind.
Strategic and Other Missions	
Cassini —1997 (Extended) in partnership with ESA and Italy	Completed its first extended mission at Saturn in 2010; its second mission extension will allow for the first study of a complete seasonal period. (A Saturn year is 30 Earth years).
Rosetta —2004 (Prime) ESA mission with U.S. participation	An orbiter and lander that will investigate the origin of comets. Will rendezvous with Comet 67P/Churyumov-Gerasimenko and remain in close proximity to the icy nucleus as it plunges toward the Sun. A small lander will be released onto the surface of the comet for in situ investigations of the chemistry and formation of volatiles.
Near Earth Object Wide-field Infrared Survey Explorer (NEOWISE) —2009 (Extended)	Search for potentially hazardous NEOs. Although the solid hydrogen is gone, NEOWISE can still operate at its two shortest infrared wavelengths, returning valuable data on the numbers, orbits, sizes, and compositions of asteroids and comets.
Lunar Atmosphere and Dust Environment Explorer (LADEE) —2013 (Prime)	Orbit the Moon to characterize the atmosphere and lunar dust environment. LADEE aims to determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further surface exploration activity.



TOP LEFT: The underlying pixels in this image indicate plumes of water vapor detected over Europa's south pole in observations taken by the Hubble Space Telescope in December 2012. The superimposed image of Europa was taken by the Galileo spacecraft. *Image Credit: NASA/ESA/JPL/STScI*

BOTTOM LEFT: Comet ISON, named after the International Scientific Optical Network (the Russian instrument array that first observed the comet) comes in from the bottom right and moves out toward the upper right, getting fainter and fainter, in this time-lapse image from the ESA/NASA Solar and Heliospheric Observatory. The image of the Sun at the center is from NASA's SDO satellite. *Image Credit: ESA/NASA/SOHO/SDO/GSFC*



TOP RIGHT: Using a precision formation-flying technique, the twin GRAIL spacecraft mapped the moon's gravity field, as depicted in this artist's rendering. *Image Credit: NASA/JPL*

Current missions to outer planets include: Cassini, now in its extended mission in the Saturnian system; New Horizons, now on its way to visit Pluto in 2015; and Juno, which will arrive at Jupiter in 2016. New Horizons and Juno are missions in the New Frontiers Program.

In addition, NASA is participating with ESA in the Rosetta comet rendezvous mission.

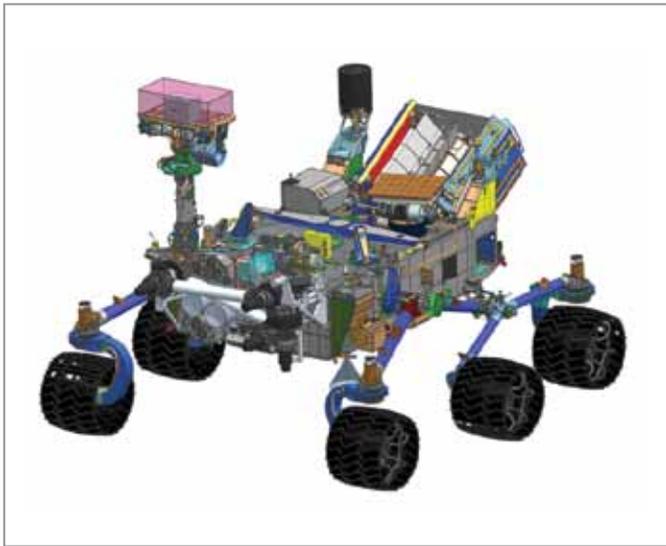
Missions in Formulation and Development

The NRC planetary science decadal survey provides science priorities and guidance that the Planetary Science Division uses to develop its portfolio of missions. The survey outlines the need for a balanced suite of Discovery, New Frontiers, and strategic missions to enable a steady stream of new discoveries and capabilities to address challenges such as potential sample return missions and outer planet exploration. In support of these objectives, NASA also collaborates with the planetary exploration programs of other countries to maximize opportunities for science, providing opportunities for NASA-led science instruments on foreign missions. Table 4.8 highlights the NASA-led missions and

Table 4.8 Planetary Science Missions in Formulation and Development

Mission—Expected Launch Year, Partners	Objective
Discovery Program	
Hayabusa 2 —2014 JAXA mission with U.S. participation	Hayabusa 2 will collect surface and possible subsurface materials from asteroid 1999 JU3 and return the samples to Earth in a capsule for analysis in 2020.
BepiColumbo —2015 ESA mission with U.S. participation	Study and understand the composition, geophysics, atmosphere, magnetosphere and history of Mercury
Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) —NLT 2016*, in partnership with France and Germany	Study the deep interior of Mars to address fundamental issues of planet formation and evolution. Investigate the dynamics of Martian tectonic activity and meteorite impacts and compare to like phenomena on Earth.
New Frontiers Program	
Origins Spectral Interpretation, Resource Identification and Security Regolith Explorer (OSIRIS-REx) —NLT 2016*, in partnership with Canada	Study near-Earth asteroid Bennu (101955), in detail, and bring back a sample to Earth in 2023. This sample will help with investigating planet formation and the origin of life, and aid in understanding asteroids that can impact Earth.
Jupiter Icy Moons Explorer (JUICE) —2022 ESA mission with U.S. participation	ESA-led joint mission with NASA to Ganymede and Jupiter system. NASA will supply one U.S.-led science instrument and hardware for two European instruments.
Mars Exploration Program	
ExoMars Trace Gas Orbiter —2016 ESA mission with U.S. participation	ESA-led joint mission with Russia; Mars orbiter with entry, descent, landing system (EDLS) tech demo; and telecom package. NASA providing Electra telecom package.
ExoMars Rover —2018 ESA mission with U.S. participation	ESA-led joint mission with Russia. NASA to provide a critical science instrument, the Mars Organic Molecule Analyzer (MOMA) mass spectrometer to the rover payload.
Mars Rover —2020 NASA mission with possible international contribution	Re-fly MSL rover and sky-crane EDLS. Rover will have different instrument suite including a caching system for future potential sample return.

* Reflects the Agency baseline commitment to launch NLT the year identified.



With the Mars Curiosity rover, NASA demonstrated a specialized landing system that delivered a ready-to-operate rover. NASA's new Mars rover, scheduled for 2020, will be much more capable than Curiosity, and will include a caching system for future potential sample return. *Image Credit: NASA*

international missions with major NASA contributions that are in formulation and development. The expected launch years are subject to change, but provide the relative timeframes for development.

Future Missions

The decadal survey identifies priorities for future planetary missions, with emphasis on maintaining a balance of Discovery, New Frontiers, and strategic missions. Work on the highest strategic mission priority has begun with the Mars Rover 2020 mission, which is now in formulation. The decadal survey ranked a mission to Europa as the second priority strategic mission, because Europa's subsurface ocean has the greatest potential to harbor extraterrestrial life. The Planetary Science Division has invested in concept studies looking at preliminary design proposals, necessary instrument technology, spacecraft design, planetary protection sterilization procedures, and instruments and systems that can withstand those procedures. In 2014, NASA will issue a Request For Information to assess options to accomplish the decadal survey scientific objectives at Europa for significantly less cost than currently considered mission concepts. The results of the studies will inform a future potential mission to Europa.

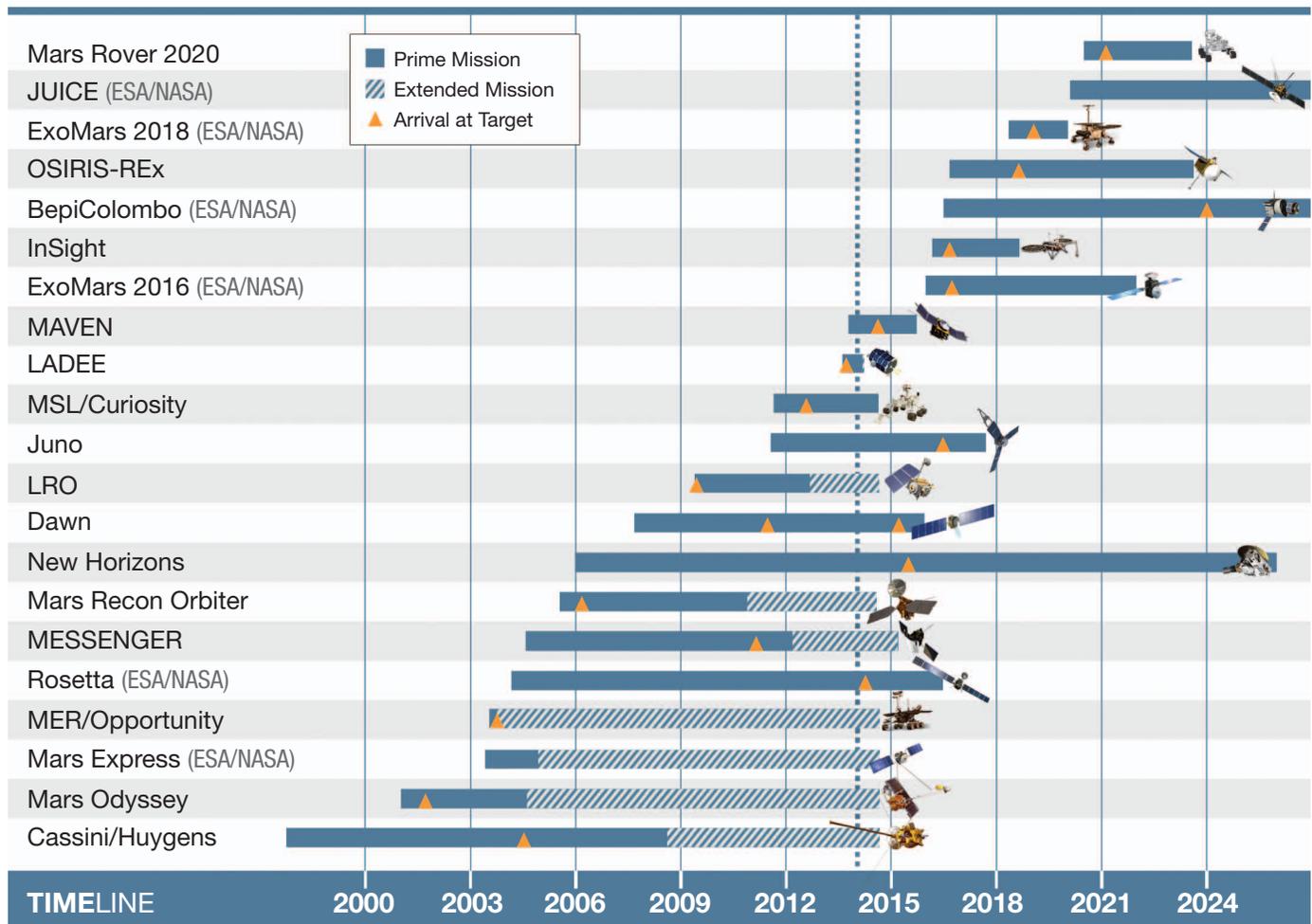
Consistent with the decadal survey priorities, and subject to the future availability of funds, the Planetary Science Division expects to implement a set of missions over the decade as outlined in Table 4.9.

Table 4.9 Future Planetary Science Missions

Mission—Expected Launch Year, Partners	Objective
Discovery Program	
Discovery—2020	Small to medium sized competed mission open to all relevant mission concepts. AO planned for FY14.
Discovery—2022	Small to medium sized competed mission open to all relevant mission concepts. AO planned for FY17.
New Frontiers Program	
New Frontiers 4—TBD	Medium sized competed missions. Candidates for concept studies will be selected from recommendations in the NRC decadal survey; Comet Surface Sample Return, Lunar South Pole-Aitken Basin Sample Return, Saturn Probe, Trojan Tour and Rendezvous, and Venus In Situ Explorer. AO not currently planned.

Figure 4.6 Summary of Planetary Science Missions

Planetary Science Timeline



Excluding MRO, MER/Opportunity, and Mars Odyssey, which are critical to current and future Mars exploration activities, the extended missions depicted in Figure 4.6 are approved for continued operations based on a senior peer review conducted by scientists every two years to determine the scientific value and priority of further mission extensions.

Technology Development

Future planetary science missions will require maintenance of existing capabilities and development of new technologies in power generation, propulsion, navigation, aerocapture, instrumentation, miniaturization, radiation hardening, planetary protection implementation, and sample acquisition, handling, return, analysis and containment. The Planetary Science Division is developing plans to guide technology investments over the next decade to ensure past investments are adequately sustained and to identify the highest

priority investments in new capabilities. The division works with STMD to guide Agency investments, and to identify opportunities to demonstrate new technologies on planetary missions. The division makes investments in future radioisotope power systems capabilities, working through the RPS Program Office at NASA's Glenn Research Center and with DOE to build current and future systems.

The Planetary Science Division manages its instrumentation technology development through two projects in the Planetary Science Research and Analysis Program:

MatISSE (Maturation of Instruments for Solar System Exploration) and PICASSO (Planetary Instrument Concepts for the Advancements of Solar System Observations). MatISSE involves mid-TRL technologies and is intended to enable timely and efficient infusion of technology into NASA planetary science missions. PICASSO focuses on low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology development to the point where the technologies may be proposed for MatISSE. Organizing all instrument technology development and demonstration projects for planetary science into these two programs has enabled better management of technology activities, and the possibility for larger awards and subsequently faster maturation timescales, specifically through MatISSE.



Artist's concept of a Mars sample return mission. *Image Credit: Wickman Spacecraft & Propulsion.*



On June 10, 2011, NASA's LRO spacecraft pointed its Narrow Angle Cameras to capture a dramatic sunrise view of Tycho crater on the Moon. *Image Credit: NASA/GSFC*

The Science That Enables **Exploration**



These superimposed photos of the Moon and a near-Earth asteroid depict the concept behind NASA's Asteroid Redirect Mission. *Image Credit: guardianlv.com*

In addition to advancing NASA's scientific goals, SMD missions and research also generate data and knowledge important to advance NASA's human exploration goals. Since Explorer I discovered the Van Allen radiation belts while orbiting the Earth, robotic missions have tested the waters for human exploration, providing useful data as either the product or byproduct of their scientific investigations. SMD partnered with the HEOMD to map the Moon's surface in unprecedented detail with LRO, and to measure the radiation environment during the cruise trip to Mars from inside the MSL spacecraft. More recently, SMD and HEOMD established SSERVI to conduct basic and applied research fundamental to understanding the Moon, Mars and its moons, near-Earth asteroids, and the near-space environments of these target bodies, while advancing human exploration of the solar system. The ISS best embodies the knowledge

gained over decades of scientific research to enable safe and productive operations in LEO. As NASA and its partners prepare for exploration beyond LEO, the question to be answered next is "what are the hazards and resources in the solar system environment that will affect the extension of human presence in space?"

NASA is currently developing the first-ever mission to redirect a near-Earth asteroid safely into the Earth-Moon system, and send astronauts to explore it. This mission will bring together the best of NASA's science, technology, and human exploration efforts to achieve the President's goal of sending humans to an asteroid by 2025. SMD's Planetary Science Research and Analysis Program will contribute to this effort by helping to identify a potential asteroid target, using ground- and space-based assets to characterize and select a candidate asteroid. NASA's existing NEO Program is exploring ways to improve detection and characterization techniques.

Furthermore, SMD's Heliophysics Division elements provide predictive capabilities essential to the protection of human and robotic explorers. The LWS and STP Programs explore the interactions between solar phenomena and planetary environments, which produce what is known as space weather. Space weather forecasting in interplanetary space is crucial to NASA's human and robotic exploration objectives beyond LEO.



4.4 Astrophysics

Strategy

Astrophysics is the study of phenomena occurring in the universe and of the physical principles that govern them. Astrophysics research encompasses a broad range of topics, from the birth of the universe and its evolution and composition, to the processes leading to the development of planets and stars and galaxies, to the physical conditions of matter in extreme gravitational fields, and to the search for life on planets orbiting other stars. In seeking to understand these phenomena, astrophysics science embodies some of the most enduring quests of humankind.

Through its Astrophysics Division, NASA leads the nation on a continuing journey of transformation. From the development of innovative technologies, which benefit other areas of research (e.g., medical, navigation, homeland security, etc.), to inspiring the public worldwide to pursue STEM careers through its stunning images of the cosmos taken with its Great Observatories, NASA's astrophysics programs are vital to the nation.

NASA's strategic objective in astrophysics is to **discover how the universe works, explore how it began and evolved,**

and search for life on planets around other stars. Three broad scientific questions flow from this objective:

- How does the universe work?
- How did we get here?
- Are we alone?

Each of these questions is accompanied by a science goal that shapes the Astrophysics Division's efforts towards fulfilling NASA's strategic objective:

- Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity
- Explore the origin and evolution of the galaxies, stars and planets that make up our universe
- Discover and study planets around other stars, and explore whether they could harbor life

The scientific priorities for astrophysics are outlined in the NRC decadal survey *New Worlds, New Horizons in Astronomy and Astrophysics* (NRC, 2010). These priorities



include understanding the scientific principles that govern how the universe works; probing cosmic dawn by searching for the first stars, galaxies, and black holes; and seeking and studying nearby habitable planets around other stars.

The multidisciplinary nature of astrophysics makes it imperative to strive for a balanced science and technology portfolio, both in terms of science goals addressed and in missions to address these goals. All the facets of astronomy and astrophysics—from cosmology to planets—are intertwined, and progress in one area hinges on progress in others. However, in times of fiscal constraints, priorities for investments must be made to optimize the use of available funding. NASA uses the prioritized recommendations and decision rules of the decadal survey to set the priorities for its investments.

NASA's Astrophysics Division has developed several strategies to advance these scientific objectives and respond to the recommendations outlined in the decadal survey on a time horizon of 5-10 years. The successful development of JWST is an Agency priority. Since its re-baseline in 2011, the project has remained on schedule and within budget for an October 2018 launch. JWST and the science it will produce

are foundational for many of the astronomical community's goals outlined in the 2010 decadal survey. NASA's highest priority for a new strategic astrophysics mission is the Wide Field Infrared Survey Telescope (WFIRST), the number one priority for large-scale missions of the decadal survey. NASA plans to be prepared to start a new strategic astrophysics mission when funding becomes available. NASA also plans to identify opportunities for international partnerships, to reduce the Agency's cost of the mission concepts identified, and to advance the science objectives of the decadal survey. NASA will also augment the Astrophysics Explorer Program to the extent that the budget allows. Furthermore, NASA will continue to invest in the Astrophysics Research Program to develop the science cases and technologies for new missions and to maximize the scientific return from operating missions.

The NASA Astrophysics Division has laid out its strategy for advancing the priorities of the decadal survey in its *Astrophysics Implementation Plan* (NASA SMD Astrophysics Division, 2012). With substantial input from the astrophysics community, the NASA Advisory Council's Astrophysics Subcommittee has developed an astrophysics visionary

roadmap (NAC Science Committee Astrophysics Subcommittee, 2013) to examine possible futures of the discipline in the longer term.

Challenges

The Astrophysics Division faces many of the same challenges in carrying out the *NASA 2014 Science Plan* as other SMD divisions; these common challenges are described in chapter 3. Some of these challenges particularly impact the Astrophysics Division's programs. There are also some challenges that are specific to the Astrophysics Division, and many of them arose after the completion of the 2010 decadal survey.

The budget environment assumed by the decadal survey has not been realized. In reality, it will be impossible to implement all the decadal survey recommendations within the decade. As described in the *Astrophysics Implementation Plan*, the Astrophysics Division has initiated studies for several versions of WFIRST.

In 2011, but following the decadal survey, NASA established a new launch date and cost commitment for JWST. The executive branch has made the successful completion and launch of JWST an Agency priority. NASA has committed funding with adequate reserves to JWST development to ensure a launch in 2018. Because of budget limitations and the need to focus on JWST, no new strategic astrophysics missions can be started until funds become available near or following the completion and launch of JWST.

NASA's international partners are pursuing new astrophysics missions that address areas of science that are recommended in the decadal survey; they provide an opportunity for the U.S. to leverage its spaceflight investments by partnering on some of these missions. The implementation of these missions, however, may represent a challenge. Aligning schedules and priorities with potential partners, as well as the restrictions on partnerships due to export control regulations like ITAR, contribute to this challenge.

With the current and anticipated constrained budget, trade-offs may need to be made across the various astrophysics research areas, potentially impacting the balance of programs. It will also be challenging to continue to support all

the highly meritorious science and technology investigations proposed, while still providing opportunities to develop the workforce, especially early-career scientists.

Implementation

The Astrophysics Division implements its astrophysics science through three focused and two crosscutting programs. The focused programs—Physics of the Cosmos, Cosmic Origins, and Exoplanet Exploration—provide an intellectual framework for advancing science and strategic planning, with each program primarily addressing one of the three broad scientific questions outlined above. Each focused program comprises one or more missions in formulation, development, and/or operation, as well as the strategic research and technology development necessary to realize future strategic missions. Two crosscutting programs complement the focused programs: the Astrophysics Explorers Program, which develops and operates smaller, PI-led missions, and the Astrophysics Research Program, which supports basic and applied research activities, including suborbital flight investigations, as well as the development and maturation of technologies for future strategic and competed missions.

Physics of the Cosmos Program

This program addresses the most extreme physical conditions of the universe and the study of the building blocks of the universe at the most basic level: the space, time, matter, and energy that constitute it. The scope of the Physics of the Cosmos Program includes understanding birth and evolution of the universe (dark energy and cosmic microwave background), the conditions of matter in strong gravitational fields and the hot universe (X-rays and Gamma-rays), and the detection and characterization of gravitational waves from space.

Cosmic Origins Program

This program seeks to understand how the universe has evolved since the Big Bang, and how its constituents were produced—the familiar night sky we see today, the planet we live on, and all the chemical elements that sustain life. To explore these topics, NASA's Cosmic Origins space telescopes explore the origin and evolution of the galaxies, stars, and planets that make up our universe.

Figure 4.7 NASA Astrophysics Missions



Exoplanet Exploration Program

This program seeks to discover and study planets orbiting around other stars. Since the first exoplanet was discovered in 1992, there has been explosive growth in the number of exoplanets identified. The Exoplanet Exploration Program aims at discovering planets around other stars, characterizing their properties, and identifying candidates that could harbor life.

Astrophysics Explorer Program

Smaller, PI-led astrophysics missions and missions of opportunity are competitively selected under the Astrophysics Explorer Program. Astrophysics Explorer missions provide opportunities for innovative science and fill the scientific gaps between the larger missions, while addressing a wide range of science topics. The Astrophysics Explorer Program also provides opportunities for smaller MoOs.

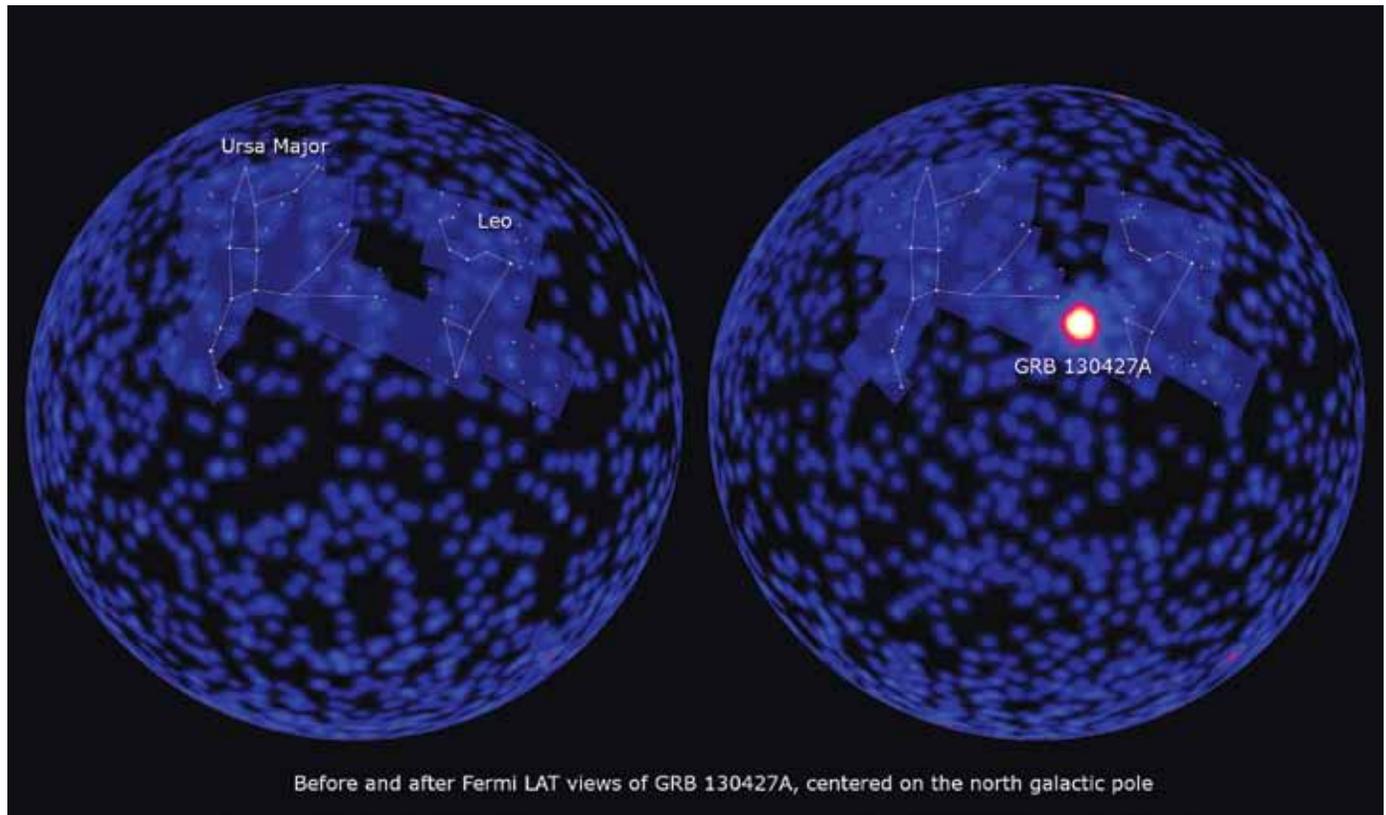
Astrophysics Research Program

Sponsored basic and applied research programs prepare for the next generation of missions through both theoretical research and applied technology investigations. They also exploit data from current missions and use suborbital science investigations to advance NASA's science goals. Suborbital investigations, an integral part of the astrophysics research program, include sounding rocket and balloon campaigns that provide new scientific discoveries, demonstrate measurement technologies, and train future mission PIs, scientists, and engineers. Astrophysics research investigations are competitively solicited through the ROSES NASA Research Announcement. Basic and applied astrophysics research investigations are essential for maximizing scientific return, pioneering new approaches to advancing the science objectives, and developing the workforce required to ensure future competitiveness.

Current Missions

Current astrophysics missions include three Great Observatories originally planned in the 1980s, launched over the past 20 years, and continuing to deliver science results in the extended operation phase. The suite of operating Great Observatories includes the Hubble Space Telescope (HST), the Chandra X-ray Observatory, and the Spitzer Space Telescope. Innovative Astrophysics Explorer missions such as the Swift Gamma-ray Explorer and NuSTAR complement these strategic missions. Many of these missions have achieved their prime science goals, but continue to produce spectacular results in their extended operation phases. Table 4.10 provides a complete list of the currently operating missions in Astrophysics.

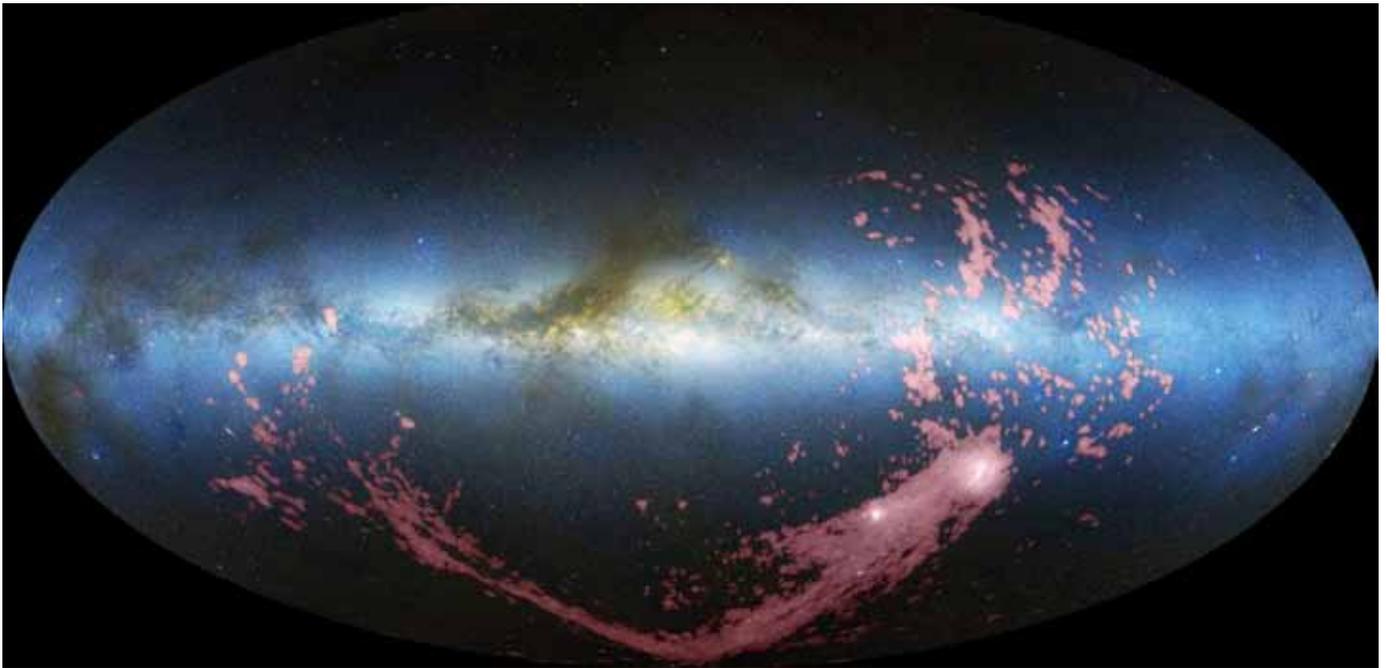
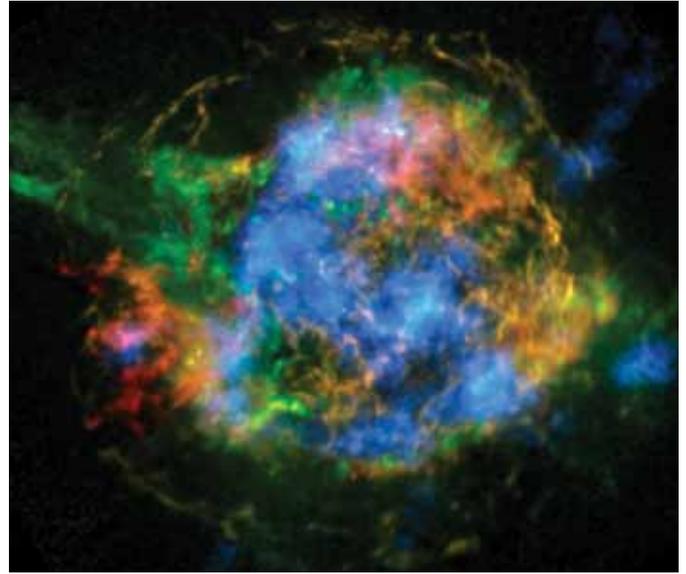
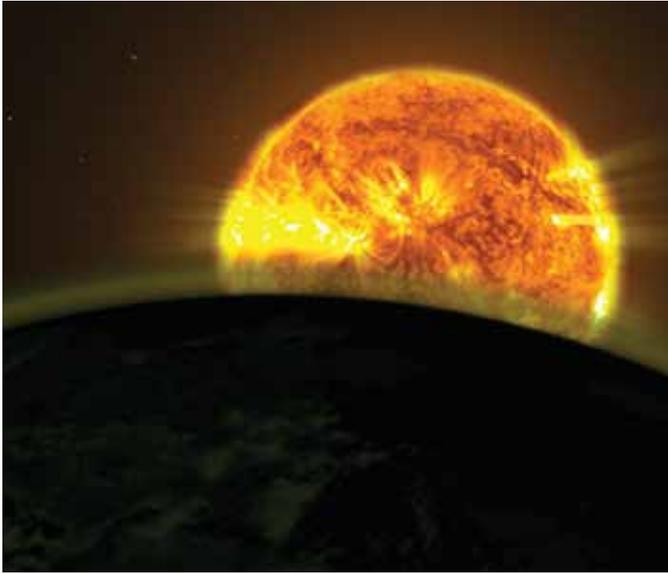
The Kepler Space Telescope is a medium-size mission launched in March 2009 to determine the frequency of Earth-like planets in orbit around other Sun-like stars. Kepler has revolutionized our knowledge about extrasolar planets in the Milky Way galaxy, including the discovery that most stars have planetary systems and that small, rocky extrasolar planets are common. In May 2013, the Kepler spacecraft lost the second of four gyroscope-like reaction wheels, which are used to precisely point the spacecraft, ending new data collection for the original mission. In 2014, the Astrophysics Division will review continued operation of all operating missions, including a revised Kepler mission, in a competitive senior review, and decisions will be made regarding the future of Kepler and other operating missions.



On April 27, 2013, NASA satellites, working in concert with ground-based telescopes, captured never-before-seen details of gamma-ray bursts (GRB) that challenge current theories of how gamma-ray bursts work. These maps show the sky at energies above 100 MeV as seen by NASA Fermi's Large Area Telescope. Left: The sky during a 3-hour interval before GRB 130427A. Right: A 3-hour map ending 30 minutes after the burst. *Image Credit: NASA*

Table 4.10 Current Astrophysics Missions

Mission—Expected Launch Year, Partners	Objective
Physics of the Cosmos Program	
Chandra X-ray Observatory —1999 (Extended) in partnership with the Netherlands	X-ray observatory that detects X-ray emission from very hot regions of the Universe such as exploded stars, clusters of galaxies, and matter around black holes.
X-ray Multi-Mirror Mission (XMM-Newton) —1999 (Extended), ESA mission with U.S. participation	X-ray observatory that detects and studies celestial X-ray sources. NASA provided elements of XMM-Newton’s instrument package.
Fermi Gamma-ray Space Telescope (Fermi) —2008 (Extended) in partnership with DOE, France, Germany, Italy, Japan, and Sweden	Gamma-ray observatory that detects gamma-rays from the most energetic regions of the universe including particle jets accelerated from black holes, powerful magnetic fields of neutron stars, and antimatter bubbles at the center of the Milky Way galaxy.
Cosmic Origins Program	
Hubble Space Telescope (HST) —1990 (Prime) in partnership with ESA	Ultraviolet/visible/near-infrared observatory that provides astronomers with the capability of measuring the acceleration of the universe, observing the formation of planetary systems, and detecting the atmospheric signatures of planets orbiting other stars.
Spitzer Space Telescope —2003 (Extended)	Infrared observatory that obtains images and spectra to provide scientists a unique view of the universe and to look into regions of space that are hidden from visible telescopes.
Stratospheric Observatory for Infrared Astronomy (SOFIA) —2010 (Prime) in partnership with Germany	Largest airborne observatory in the world, it makes mid and far infrared observations that are impossible for ground-based telescopes. SOFIA is used to study astronomical phenomena such as star birth and death.
Exoplanet Exploration Program	
Kepler Space Telescope —2009 (TBD)	High precision optical photometer capable of continuously measuring the brightness of 150,000 stars in order to detect the tiny dimming caused when a planet transits in front of its parent star.
Astrophysics Explorer Program	
Swift —2004 (Extended) in partnership with Italy and the United Kingdom	A multi-wavelength observatory dedicated to the study of Gamma-ray burst (GRB) science. Swift’s three instruments have worked together to observe GRBs and afterglows in the gamma ray, X-ray, ultraviolet, and optical wavebands.
Suzaku —2005 (Extended) in partnership with Japan	Japanese satellite providing scientists with information to study events in the X-ray energy range. NASA provided one of Suzaku’s three instruments.
Nuclear Spectroscopic Telescope Array (NuSTAR) —2012 (Prime) in partnership with Denmark and Italy	High-energy X-ray telescope that is the first focusing high-energy X-ray telescope to orbit Earth and is capable of, among other things, measuring the spin of supermassive black holes and mapping the heavy elements created in a supernova explosion.



TOP LEFT: In 2013, using the NASA Hubble Space Telescope Wide Field Camera 3, two teams of scientists found faint signatures of water in the atmospheres of five distant planets. This is the first study to conclusively measure and compare the profiles and intensities of these signatures on multiple worlds. To determine what is in the atmosphere of an exoplanet, astronomers watch the planet pass in front of its host star and look at which wavelengths of light are transmitted and which are partially absorbed. This illustration shows a star's light illuminating the atmosphere of a planet. *Image Credit: NASA/GSFC*

TOP RIGHT: One of the biggest mysteries in astronomy, how stars blow up in supernova explosions, is finally being unraveled with the help of NASA's

NuSTAR spacecraft. The high-energy X-ray observatory has created the first map of radioactive material in a supernova remnant. The results, from a remnant named Cassiopeia A, reveal how shock waves likely rip apart massive dying stars. *Image Credit: NASA/Caltech*

BOTTOM: Astronomers using the NASA/ESA Hubble Space Telescope have solved the 40-year-old mystery of the origin of the Magellanic Stream, a long ribbon of gas (the pink stream in this image) stretching nearly halfway around the Milky Way. New Hubble observations reveal that most of this stream was stripped from the Small Magellanic Cloud some two billion years ago, with a smaller portion originating more recently from its larger neighbour. *Image Credit: NASA/STScI*

Missions in Formulation and Development

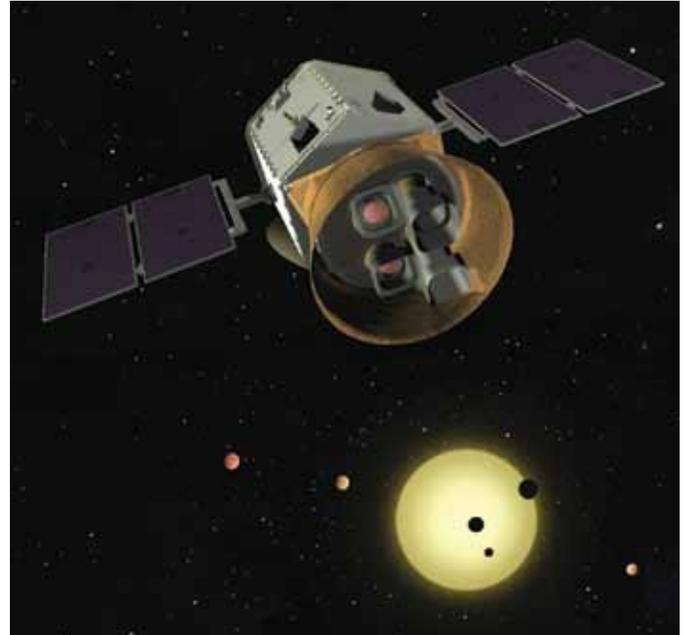
JWST, the next astrophysics strategic mission, is under development and on schedule to be launched in 2018. In addition to JWST, NASA is also developing the Astrophysics Explorer missions Transiting Exoplanet Survey Satellite (TESS) and Neutron star Interior Composition Explorer (NICER), partnering with ESA on the Laser Interferometer

Space Antenna (LISA) Pathfinder and Euclid missions, and completing the Soft X-ray Spectrometer instrument for JAXA's ASTRO-H mission. NICER is partially funded by STMD to support tools for celestial navigation applications of pulsars. Table 4.11 identifies the missions that are in formulation or development, with launches planned over the 2014–2020 timeframe. The expected launch years are subject to change, but provide the relative timeframes for development.

Table 4.11 Astrophysics Missions in Development or Formulation

Mission—Expected Launch Year, Partners	Objective
Cosmic Origins Program	
James Webb Space Telescope (JWST) —NLT 2018* in partnership with ESA and Canada	Infrared successor to Hubble to image first light after the Big Bang and the first galaxies to form in the early universe. Top-ranked space-based “Major Initiative” in the 2001 decadal survey.
Physics of the Cosmos Program	
Laser Interferometer Space Antenna (LISA) Pathfinder —2015 ESA mission with U.S. participation	Flight demonstration of key technologies for future space-based gravitational wave observatories. NASA provides colloidal micronewton thrusters and a drag-free dynamic controller.
Euclid —2020 ESA mission with U.S. participation	Visible/near infrared observatory to study dark energy. NASA provides detector subsystems for the Near Infrared Spectrophotometer instrument.
Astrophysics Explorer Program	
ASTRO-H —NLT 2016* JAXA mission with U.S. participation	X-ray observatory to study material in extreme gravitational fields. NASA provides X-ray optics and a Soft X-ray Spectrometer, the primary instrument for JAXA's ASTRO-H observatory.
Neutron Star Interior Composition Explorer (NICER) —NLT 2017*	High precision array of X-ray photometers mounted on the International Space Station to explore the exotic states of matter within neutron stars and reveal their interior and surface compositions. Data will also be used to demonstrate pulsar navigation techniques for STMD.
Transiting Exoplanet Survey Satellite (TESS) —2018	Array of cameras to discover transiting exoplanets ranging from Earth-sized to gas giants, in orbit around the nearest and brightest stars in the sky. Will find exoplanets as targets for JWST follow-up observations.

* Reflects the Agency baseline commitment to launch NLT the year identified.



TOP LEFT: A full-scale JWST sunshield membrane deployed on the membrane test fixture at ManTech International Corporation's facilities in Huntsville, Alabama, ready for a precise measurement of its three dimensional shape. The JWST sunshield comprises five of these layers, each of which has to be precisely spaced with respect to the next. *Image Credit: Northrop Grumman Aerospace Systems*

TOP RIGHT: TESS is an Explorer-class planet finder. In the first-ever spaceborne all-sky transit survey, TESS will identify planets ranging from Earth-sized to gas giants, orbiting a wide range of stellar types and orbital distances. *Image Credit: NASA/GSFC*



BOTTOM LEFT: The first six flight-ready JWST primary mirror segments are prepped to begin final cryogenic testing at NASA's Marshall Space Flight Center in Huntsville, Alabama. *Image Credit: NASA/Chris Gunn*

Future Missions

Table 4.12 identifies the future potential missions for Astrophysics. One important goal of the Astrophysics Division is to begin a strategic mission, subject to the availability of funds, which is responsive to the decadal survey and is launched after JWST. To this end, and as detailed in the *Astrophysics Implementation Plan*, the division is undertaking a specific series of actions to put in place the planning needed prior to initiating a strategic mission. In 2011–2012, detailed studies of mission concepts for WFIRST, the top priority of the decadal survey in the large mission class, were conducted by the astrophysics community. These efforts

Table 4.12 Future Astrophysics Missions

Mission—Expected Launch Year, Partners	Objective
Physics of the Cosmos Program	
L2—2028 ESA mission with possible U.S. participation	An ESA advanced X-ray observatory to study the hot and energetic universe. NASA will participate in concept studies with ESA and discuss contributing to the mission.
Exoplanet Exploration Program	
Wide Field Infrared Survey Telescope (WFIRST)/ Astrophysics Focused Telescope Assets (AFTA) —TBD NASA mission with possible international contribution	A widefield visible/near infrared observatory to study dark energy, exoplanets, and galactic structure. Several concepts are being studied, including a 2.4m version using existing telescope assets and an optional coronagraph.
Astrophysics Explorer	
Astrophysics Explorer— ~2020	Small to medium sized competed mission or MoO. AO planned for FY14.
Astrophysics Explorer—early/mid 2020s	Small to medium sized competed mission or MoO. AO ~2016-17.
Astrophysics Explorer—mid 2020s	Small to medium sized competed mission or MoO. AO ~2019-20.

produced two reports: one describing a full version of the WFIRST as recommended by the decadal survey (including a 1.3 m telescope), and a second report describing a probe-size version, which is capable of addressing many of the full-size WFIRST mission objectives for reduced cost. After certain 2.4 m telescope assets were made available to NASA, in 2012–2013, the division established a Science Definition Team (SDT) and pre-formulation study to investigate possible use of these assets to address WFIRST science—namely, dark energy, exoplanets, and an infrared (IR) survey of the Milky Way galaxy. The study team is also investigating the potential inclusion of a coronagraph to the mission to address the New Worlds priorities of the decadal survey.

In 2013, the Astrophysics Division also started Science and Technology Definition Team studies for several smaller, probe-class mission concepts to respond to the other priorities in the decadal survey. These studies included exoplanet probes and an X-ray probe. Following ESA’s selection of “The Hot and Energetic Universe” (to be addressed by an advanced X-ray observatory) as the theme of their next large mission for launch in 2028, and concurrent with NASA’s

interest in contributing to ESA’s advanced X-ray observatory to fulfill the decadal survey recommendations for an International X-ray Observatory (IXO), NASA will no longer pursue the option of a probe-size X-ray mission.

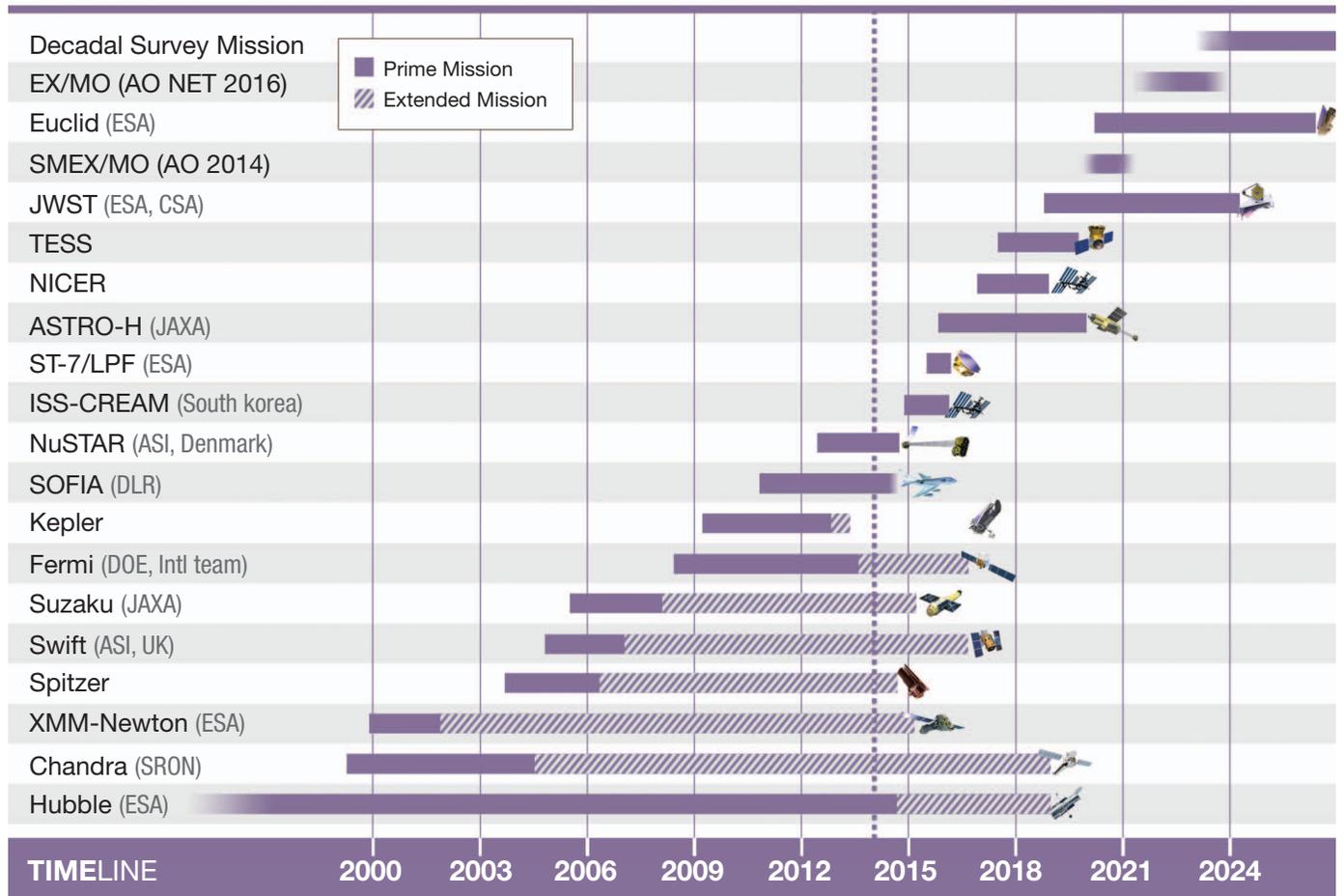
ESA has also chosen “The Gravitational Universe” as the theme of its subsequent large mission for launch in 2034; NASA has expressed interest in contributing to ESA’s gravitational wave observatory to fulfill decadal survey recommendations for a LISA mission.

Another important goal of the Astrophysics Division is to augment the Astrophysics Explorer Program. The decadal survey recommends that four missions and four smaller MoOs be selected over the decade. The division plans two or three AOs during the remainder of the decade, with the intent of selecting one mission and one MoO from each AO. One such AO will be issued in fall 2014 with the goal of down-selecting a mission in 2016.

Looking towards the longer term, the astrophysics visionary roadmap provides a compelling 30-year vision for astrophysics at NASA. The roadmap takes a long-range

Figure 4.8 Summary of Astrophysics Science Missions

Astrophysics Timeline



Excluding the Great Observatories HST and Chandra, the extended missions depicted in Figure 4.8 are approved for continued operations based on a senior peer review conducted by scientists every two years to determine the scientific value and priority of further mission extensions.

view, highlights science possibilities over the next 30 years, and provides the inspiration and rationale for continuing American leadership and investment in NASA's astrophysics programs.

Technology Development

The Astrophysics Division supports development of technologies for its future missions primarily through two program elements: the Astrophysics Research and Analysis (APRA) element of the Astrophysics Research Program, and Strategic Astrophysics Technology (SAT) elements in the three focused programs (Cosmic Origins, Exoplanet Exploration,

Physics of the Cosmos). The recently initiated SAT elements support research and technology efforts in each program, and aim to bring promising technologies closer to flight readiness. Both APRA and SAT are competitive activities; grants are awarded competitively via a process of peer review based on the science and technical merits of the submitted proposals, and the strategic priorities of the division as set by the decadal survey. The SAT element also includes directed technology development efforts.

The APRA element supports development of low- to mid-TRL technologies, as well as instrument feasibility studies, and proof of concept efforts. The APRA element also

supports development of instruments for suborbital flight opportunities including scientific balloons and sounding rockets. The SAT element focuses on mid-TRL technologies, and brings these technologies to maturation for infusion into astrophysical missions. Technologies that are supported by the APRA and SAT elements are strongly tied to the broad science questions addressed by the Astrophysics Division's three focused programs. Examples of areas funded by SAT and APRA include IR and X-ray detectors, optical/ultraviolet mirror coatings, X-ray optics, lasers, and micro thrusters for gravitational wave studies.

NASA is partnering with ESA to develop and test technologies necessary for a future gravitational wave observatory. ESA's LISA Pathfinder mission is a technology demonstration mission, and NASA is providing colloidal micronewton thrusters and a drag-free dynamic controller to be co-manifested with ESA's LISA Test Package.

Development of technology relevant to future astrophysics missions also benefits from investments made by STMD. STMD is contributing to basic and innovative technology relevant to future operating missions, as well as developing technology for two potential missions—the Station Explorer for X-ray Timing and Navigation (SEXTANT) for NICER and a potential coronagraph for WFIRST. SEXTANT will use the pulsar timing information collected by NICER to perform a flight demonstration of pulsar navigation techniques. The WFIRST SDT has concluded that a WFIRST mission could be enhanced by the addition of a coronagraph for direct imaging of nearby exoplanets. STMD is partnering with the Astrophysics Division to mature the technologies required for two candidate coronagraph architectures for possible infusion into a WFIRST coronagraph.

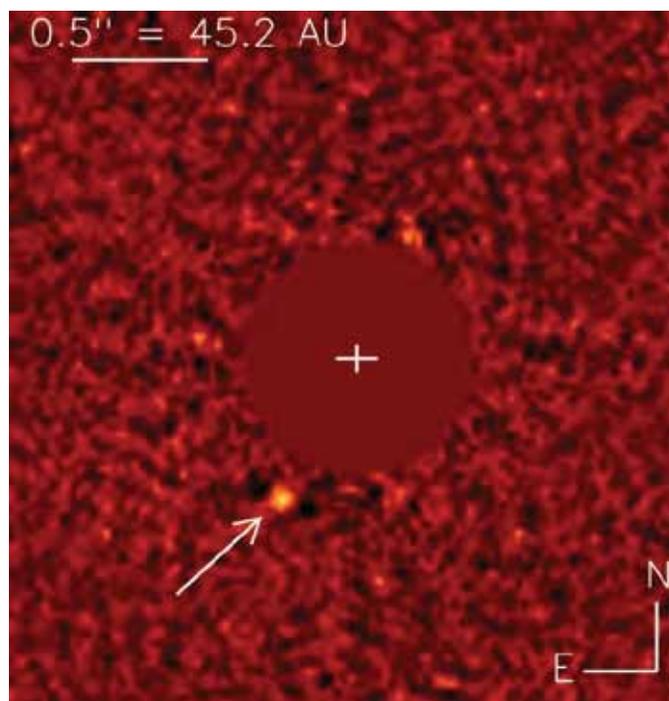
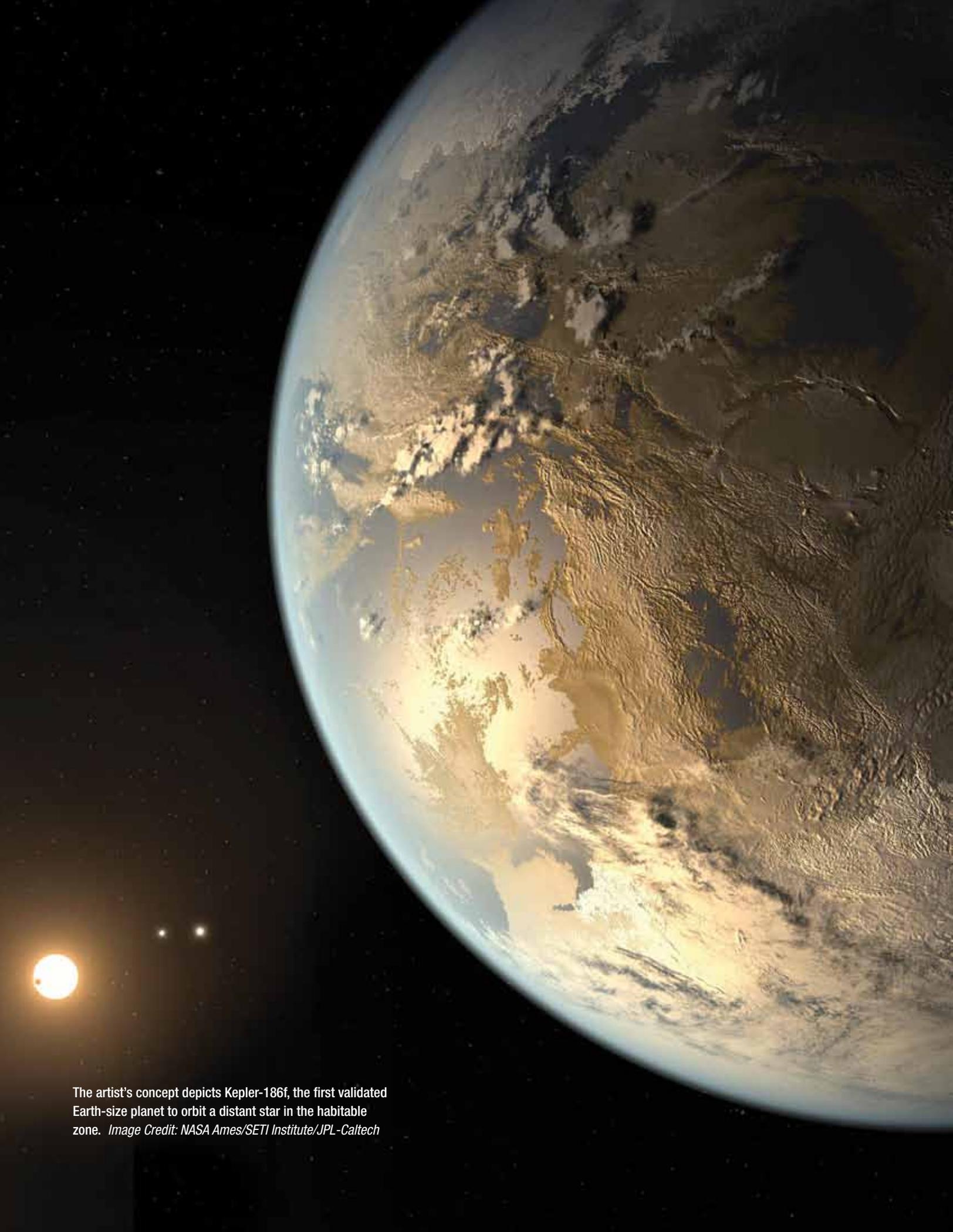


Image of the newly discovered planet, HD 95086 b. The star, which the planet orbits, has been blocked out by a coronagraph and the diffraction patterns removed during data reduction. *Image Credit: ESO/MLT and Rameau et al*



The artist's concept depicts Kepler-186f, the first validated Earth-size planet to orbit a distant star in the habitable zone. *Image Credit: NASA Ames/SETI Institute/JPL-Caltech*

Interdisciplinary Studies of **Exoplanets:**

Crosscutting Work Between the Astrophysics and Planetary Science Divisions

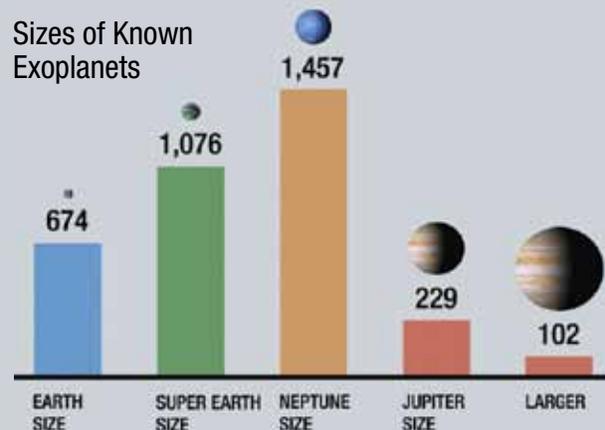
Exoplanets are currently a topic studied in both SMD's Planetary Science and Astrophysics Divisions at NASA, and are a priority according to the decadal surveys of both disciplines. The Planetary Science Division's Research and Analysis Program and the Astrophysics Division's Exoplanet Exploration Program coordinate their studies of exoplanets to determine the origins of stellar systems that are similar to our own.

The specific goals of the Astrophysics Division include searching for planets and planetary systems around stars in our galaxy, determining the percentage of planets that are in or near the habitable zone of a wide variety of stars, and characterizing planets around other stars for their habitability and other physical characteristics. The Planetary Science Division's specific goals include understanding the origin and evolution of the atmospheres of planets and their satellites, understanding the formation and early evolution of planetary systems, and providing the fundamental research and analysis necessary to characterize those planetary systems, including their habitability. While the Astrophysics Division emphasizes observational detection and study of exoplanets, the Planetary Science Division primarily focuses on the knowledge necessary for understanding exoplanets through modeling, data analysis, theoretical studies, and ground-based observations.

The two divisions have cooperated on several exoplanet research efforts:

- The Kepler mission was developed as a Discovery Program Mission in the Planetary Science Division and is now run by the Astrophysics Division as part of the NASA Exoplanet Exploration Program. Launched in 2009, Kepler is a spaceborne photometer designed to survey distant stars to determine the prevalence of Earth-like planets. Utilizing data

Sizes of Known
Exoplanets

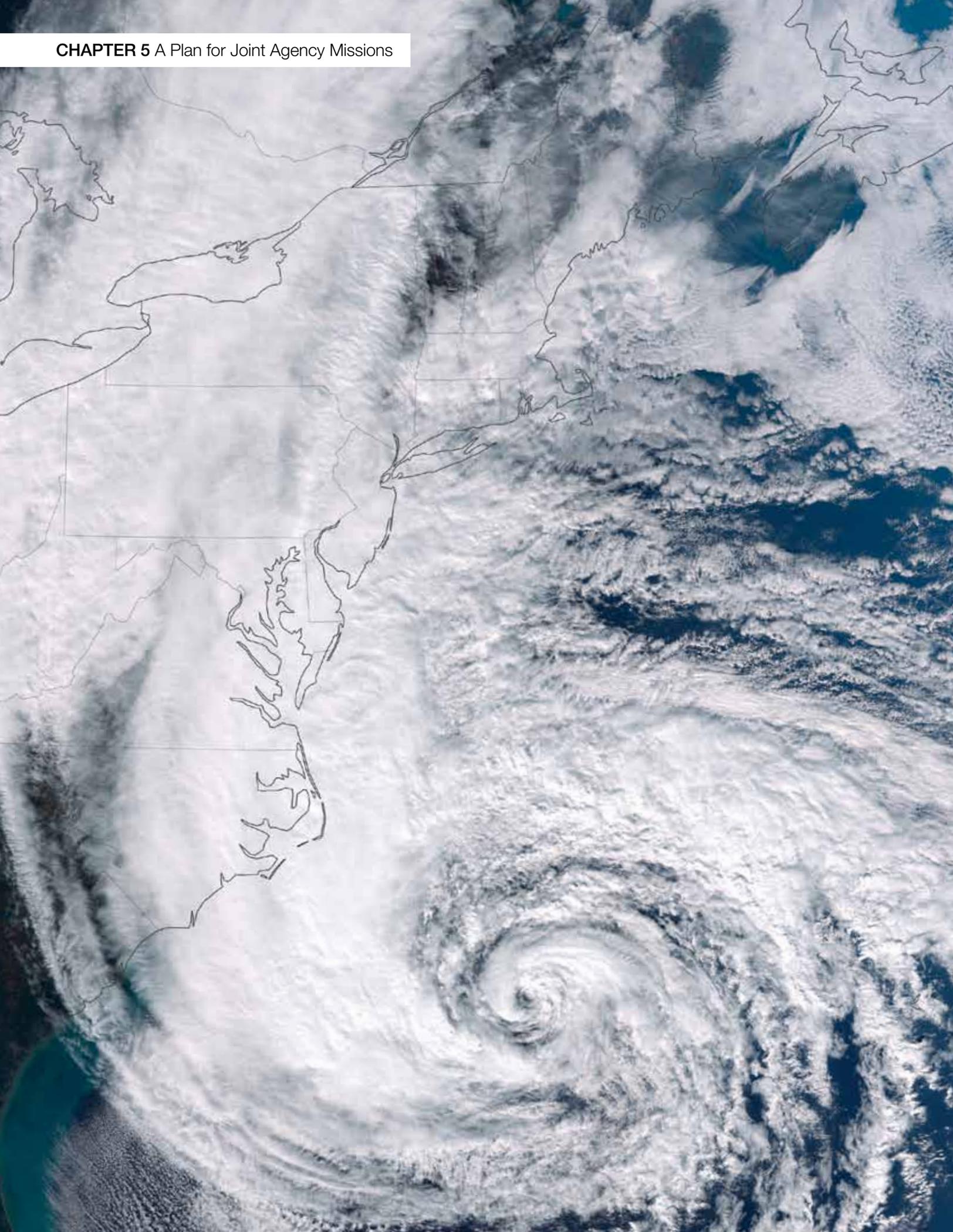


Candidate exoplanets discovered by the Kepler Space Telescope sorted by exoplanet size. Includes all Kepler-discovered exoplanets as of November 2013.

from the Kepler mission, scientists are approaching confirmation of the existence of almost 2000 planets that orbit stars other than our Sun.

- The Planetary Science Division provides the baseline parameters that the Astrophysics Division looks for with its Exoplanet Exploration Program missions.
- The NASA Astrobiology Institute, a virtual institute jointly funded by the Planetary Science Division and the Astrophysics Division, currently includes the Virtual Planetary Laboratory that is exclusively focused on exoplanets.

Working together, the Planetary Science and Astrophysics Divisions hope to lead humankind on a voyage of unprecedented scope and ambition, promising insight into two of our most timeless questions: Where did we come from? Are we alone?



CHAPTER 5

A Plan for **Joint Agency** Missions

This chapter outlines the Joint Agency Satellite Division (JASD)—an SMD organization with broad crosscutting responsibilities. In partnership with NOAA, JASD manages the development and launch

of several operational environmental monitoring satellite programs, projects, and instruments on a reimbursable basis.

LEFT: The Suomi NPP satellite acquired this natural-color image of Hurricane Sandy on October 28, 2012. *Image Credit: NASA/GSFC/CIMSS and J. Allen*



Joint Agency Satellite Division

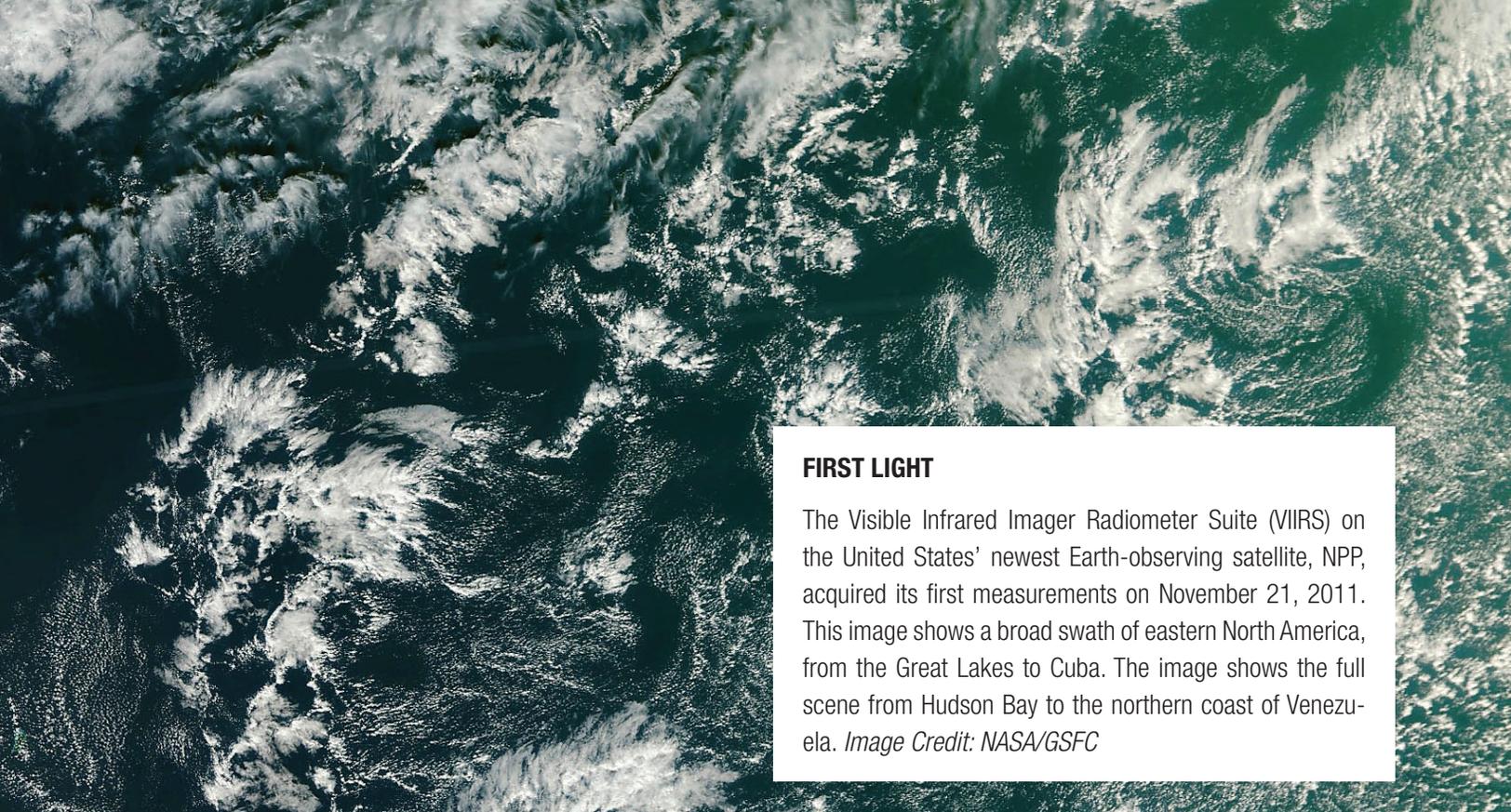
Strategy

JASD implements the nation's space policy for environmental Earth observation and weather (as documented in the President's National Space Policy) by managing in partnership with NOAA the acquisition of several operational L1, geostationary, and polar satellite programs, projects and instruments. JASD helps to achieve the NRC recommendations on Earth science and heliophysics observations. The NRC stated in its 2007 Earth science decadal survey that "sustained measurements of . . . key climate and weather variables are part of the committee's strategy to achieve its vision for an Earth observation and information system in the next decade." In 2012, the NRC stated in its heliophysics decadal survey that it "recommends that NASA, NOAA and the Department of Defense work in partnership to plan for the continuity of solar and solar wind observations beyond the lifetimes of ACE, SOHO, STEREO, and SDO." JASD advances these efforts by working with other agencies to obtain such measurements through the management and oversight of the Joint Polar Satellite System (JPSS) Program, the Geostationary Observational Environmental Satellite (GOES)-R Series Program, the Joint Altimetry Satellite Oceanography Network (JASON) 3 project, and the DSCOVR project, and by providing instruments for the

European Organisation for the Exploitation of Meteorological Satellites' (EUMETSAT) Meteorological Operational (MetOp) satellite program via NOAA's international agreements.

SMD established JASD in April 2010, following an executive branch decision to replace the National Polar-orbiting Operational Environmental Satellite System (NPOESS) with the NOAA/NASA JPSS and the DOD Defense Weather Satellite System (DWSS). JASD builds on NASA's history of well-managed reimbursable partnerships with NOAA, including GOES and the Polar-orbiting Operational Environmental Satellites (POES). NOAA provides the requirements and budget, and NASA is responsible for development and acquisition of the space systems—and in some cases the ground systems—following NASA's rigorous flight program and project management process. JASD funding is fully reimbursable; the only JASD-related expense NASA incurs is the employment of the NASA Headquarters employees who staff JASD.

Since its inception in 2010, JASD has consistently delivered to NASA's partner agencies and the science community. For example, Suomi NPP was the first system completed



FIRST LIGHT

The Visible Infrared Imager Radiometer Suite (VIIRS) on the United States' newest Earth-observing satellite, NPP, acquired its first measurements on November 21, 2011. This image shows a broad swath of eastern North America, from the Great Lakes to Cuba. The image shows the full scene from Hudson Bay to the northern coast of Venezuela. *Image Credit: NASA/GSFC*

and launched under JASD management. After a successful launch in October 2011 and check-out in March 2012, NASA transferred operational control of Suomi NPP to NOAA. A top priority for JASD is to ensure that Suomi NPP continues to operate optimally and is able to overlap with the planned follow-on polar orbiting weather satellite, JPSS. To that end, NASA and NOAA will continue to collaborate during the mission's five-year prime operations phase to ensure that the agencies' shared objectives are being met. The system's value is already apparent; Suomi NPP data are publicly available and are being used by the National Weather Service for weather forecasting.

In September 2012, MetOp B successfully launched carrying several U.S. instruments that were transitioned into JASD via the new partnership with NOAA. The instrument suite included the Advanced Microwave Sounding Unit-A (AMSU-A), the Advanced Very High Resolution Radiometer (AVHRR), and the Space Environment Monitor (SEM). These instruments are providing key measurements to U.S. and international meteorological and space weather communities.

The latest JASD success, TCTE, built under a NASA contract for NOAA, was launched aboard a U.S. Air Force Space Test Program Satellite-3 (STPSat-3) on the Operationally Responsive Space-3 (ORS-3) mission in November 2013. TCTE provided a means to transfer the absolute calibration of the Total Solar Irradiance (TSI) measurement, currently provided by the aging SORCE spacecraft, to the follow-on TSI measurement instrument, thus extending the 35-year record of space-based measurements on solar variations that affect Earth's weather and climate.

Implementation

JPSS Program

The JPSS Program provides continuity of critical observations for accurate weather forecasting, reliable severe storm outlooks, and global measurements of atmospheric and oceanic conditions such as sea surface temperatures, ozone, and more. JPSS also provides operational continuity of satellite-based observations and products for NOAA's POES and the Suomi NPP satellite. The program consists of the currently orbiting Suomi NPP and two planned missions,

JPSS-1 and JPSS-2, along with a ground system for satellite command and control and data acquisition, processing, and dissemination.

GOES-R Series Program

The GOES-R Series program consists of a system of environmental satellites in geostationary orbit that provide continuous weather imagery and monitoring of meteorological data for the United States, Latin America, much of Canada, and most of the Atlantic and Pacific ocean basins. The GOES-R Series satellites provide atmospheric, oceanic, climatic, and solar products supporting weather forecasting and warnings, climatologic analysis and prediction, ecosystems management, and safe and efficient public and private transportation. The GOES-R Series satellites also provide a platform for space environmental observa-

tions and auxiliary communications services that provide for GOES data rebroadcast, data collection platform relay, low resolution imagery, emergency weather communications, and satellite-aided search and rescue. The GOES-R Series Program includes spacecraft, instruments, launch services, and all associated ground system elements and operations for four satellites (GOES-R/S/T/U).

Reimbursable Projects Program

The Reimbursable Projects Program (RPP) is an uncoupled portfolio of independent projects with unique mission-specific objectives. Currently the RPP consists of follow-on missions to operational weather and climate instruments and satellites whose purpose is to continuously observe the Sun and the Earth’s atmosphere and oceans. The RPP projects include: POES/MetOp, JASON-3, and DSCOVR.

Table 5.1 NOAA Missions in Development or Formulation

Mission—Expected Launch Year, Partners	Objective
JPSS Program	
Joint Polar Satellite System (JPSS)-1 & 2—2017 & 2021	U.S. civilian operational polar satellite system providing environmental observational data to accurately predict weather three to ten days in the future
GOES-R Series Program	
Geostationary Operational Environmental Satellite-R, S, T & U (GOES-R, S, T, & U)—2016, 2017, 2019, & 2024	Next generation of U.S. operational geostationary weather satellites for meteorological and space weather monitoring
Reimbursable Projects Program	
Deep Space Climate Observatory (DSCOVR)—2015	Primary mission is to monitor space weather, with secondary mission of Earth observation.
Joint Altimetry Satellite Oceanography Network-3 (JASON-3)—2015	Will extend the next decade of continuous climate record of ocean surface topography.
Meteorological Operational (MetOp) C—2017	European contribution for the collaborative Initial Joint Polar Orbiting Operational Satellite System
Total Solar Irradiance Sensor-1 (TSIS-1) Instrument (acquisition strategy for hosting TSIS-1 is being evaluated)	Continues the 34-year record of total solar irradiance, enabling scientists to understand the causes of climate change on our planet

TOP: Jason-3 is an operational ocean altimetry mission designed to precisely measure sea surface height to monitor ocean circulation and sea level. Jason-3 will follow in the tradition of previous NASA-JPL missions such as Topex/Poseidon, Jason-1 and the Ocean Surface Topography Mission/ Jason-2. *Image Credit: CNES, CLS*

MIDDLE: Building on the success of the Suomi NPP polar-orbiting satellite, JPSS-1 will feature advanced technologies and instruments to ensure a continuous flow of Earth observations. *Image Credit: Ball Aerospace & Technologies Corp.*

BOTTOM: The advanced spacecraft and instrument technology employed by the GOES-R series will provide significant improvements in the detection and observations of environmental phenomena that directly affect public safety, protection of property, and our nation's economic health and prosperity. *Image Credit: NOAA/GOES-R.*

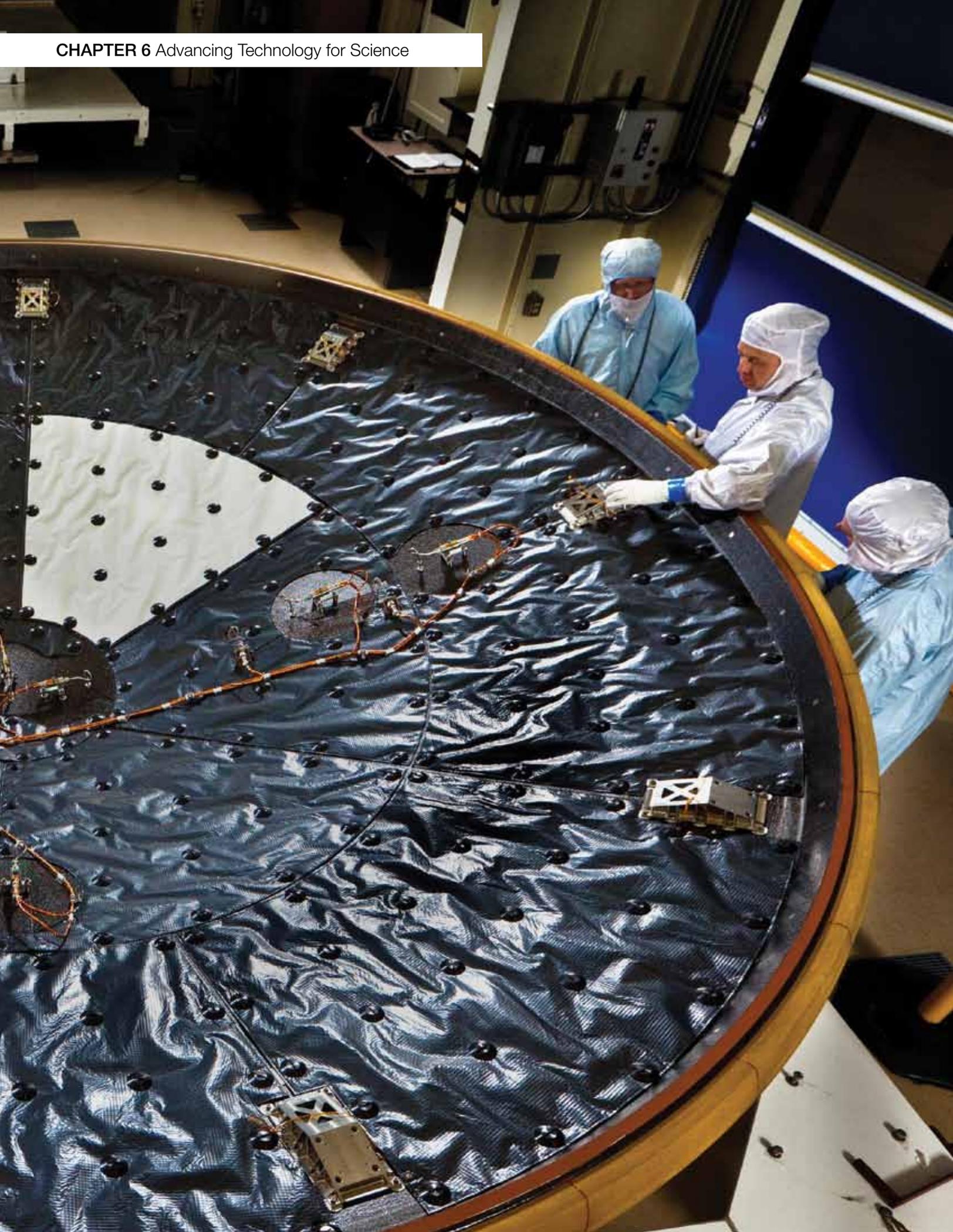


Missions in Formulation and Development

JASD fulfills the standard management and oversight role for NOAA's reimbursable satellite development missions described in Table 5.1.

Future Missions

JASD participates in strategic planning discussions with NOAA regarding future follow-on environmental monitoring operational missions. NOAA has the primary responsibility for future mission planning, requirements development, and budgeting for follow-on operational environmental monitoring missions. JASD provides expertise and advice to NOAA regarding optimum acquisition strategies and implementation concepts.



CHAPTER 6

Advancing **Technology** for Science

LEFT: The heat shield for NASA's Mars Science Laboratory is the largest ever built for a planetary mission. Technicians in the photo are installing the electronics for the Mars Science Laboratory Entry, Descent and Landing Instrument (MEDLI)—an instrument that collected data about temperature and pressure during descent through the Mars atmosphere. *Image Credit: NASA/JPL*

NASA invests in crosscutting, transformational space technologies that have high potential for offsetting mission risk, reducing cost, and advancing existing capabilities for increasingly complex and challenging missions. Drawing on talent from NASA's workforce, academia, and the broader industrial base, technological advancements enable a new class of science missions, strengthen our nation's leadership in Earth and space science, and foster a technology-based economy. NASA's investment strategy spans the entire technology lifecycle, from conceptual studies to discover new technologies (TRL 1-3), to rapid development and ground-based testing (TRL-3-5), to flight demonstration in a relevant environment (TRL 5-7). NASA implements technology development at all appropriate organizational levels in the Agency.

Two organizations are responsible for developing and implementing the Agency's technology strategy—the Office of the Chief Technologist (OCT) and STMD. OCT advises and advocates for NASA on matters concerning Agency-wide science and technology policy and programs. OCT coordinates and tracks technology investments across the Agency; develops and executes innovative technology partnerships with other government agencies, academia, and the commercial aerospace community; and leads the Agency's technology transfer and commercialization efforts.

As described in chapter 3, STMD is responsible for developing the crosscutting, pioneering, new technologies and capabilities needed by the Agency to achieve its current and future missions. Table 6.1 lists STMD's nine technology programs, and provides examples that show how each program is relevant to SMD.

At the directorate level, the SMD Chief Technologist is the SMD interface to OCT and assists in establishing appropriate Agency-level technology policy, practices, and partnerships. As the lead point-of-contact to STMD, the Chief Technologist serves as an advocate and a resource for alignment of STMD technology development with SMD science objectives.

Within the directorate, the SMD Chief Technologist is responsible for coordinating the development and utilization of technology across the four science disciplines.

Working closely with the Division Technologist in each science division, the SMD Chief Technologist establishes an understanding of the programmatic requirements for the directorate and actively searches for collaborative opportunities to advance the necessary technology within the divisions to enable future science missions.

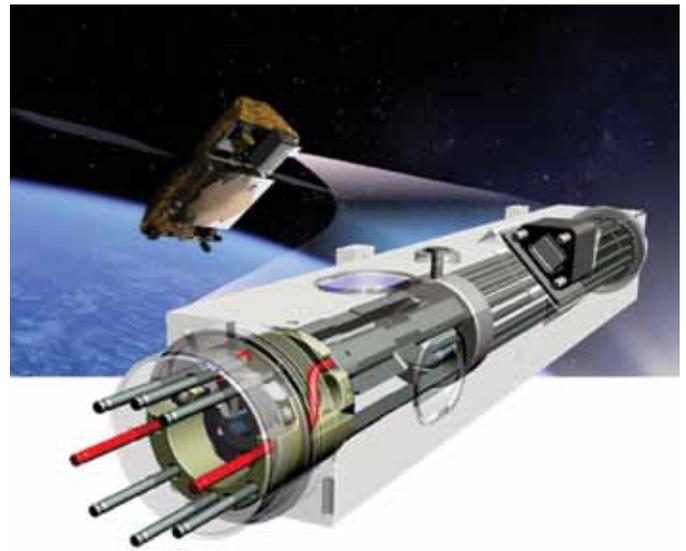
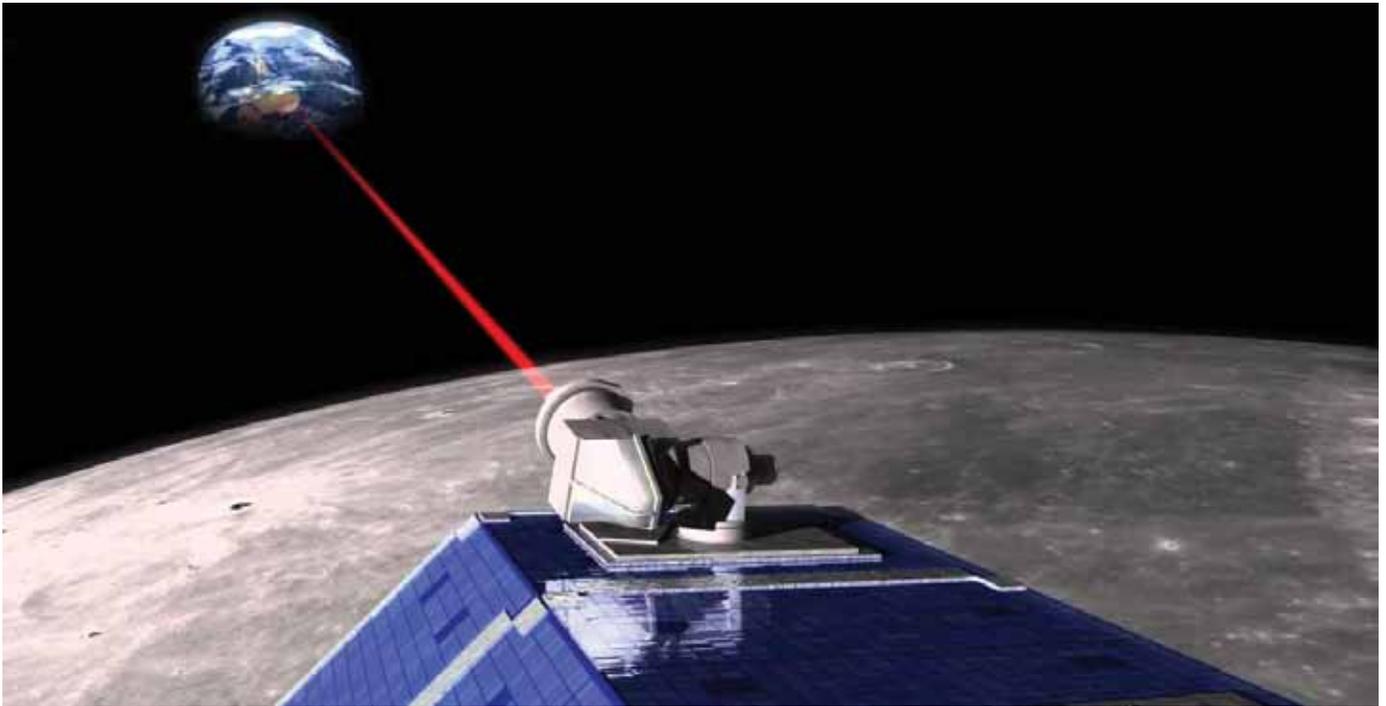
One of the primary responsibilities of the SMD Chief Technologist is to facilitate opportunities for collaboration with partners external to the directorate who share a common goal with SMD. As part of this effort, the Chief Technologist ensures such stakeholders are informed about SMD's technology requirements and planned investments. Awareness of SMD's technology development priorities could lead other organizations to make investment decisions that are beneficial to SMD, and lead to opportunities for cost sharing and other forms of partnership. At a minimum, maintaining awareness and sharing information about technology requirements and development efforts will reduce the likelihood that either partner will needlessly invest in technology areas already being explored by the other partner.

There are six primary interfaces SMD must maintain to enable collaboration with external partners and ensure advancement of technology needed to conduct Earth and space science research:

1. OCT and STMD: SMD participation in and awareness of OCT/STMD technology initiatives is necessary to increase the likelihood of successful technology infusion into future science missions.
2. Other NASA mission directorates: Common goals such as robotic and human exploration of Mars lead to opportunities for technology collaboration on common mission requirements such as entry, descent, and landing.
3. Other U.S. government agencies: Many government agencies share technology interests with SMD, including the science-based technology overlaps with NOAA, NSF, and USGS; and the remote sensing, data analysis, archiving, and mission operations systems technologies shared with several national security agencies.

Table 6.1 STMD Programs Supporting NASA Science Technology Development

STMD Technology Program	TRL Range	Examples Relevant to SMD	Future Opportunities
NASA Innovative Advanced Concepts (NIAC)	1-3	Advanced concepts such as printable spacecraft, cave-hopping robots, ultra-lightweight optics, ghost imaging	Competitive solicitation through umbrella NRA (REDDI)
Space Technology Research Grants (STRG)	1-3	Early Career Faculty/Early Stage Innovations	Competitive solicitation through umbrella NRA (REDDI)
Center Innovation Fund (CIF)	1-3	Lightweight telescope systems using novel nano-layered synthesized materials, nanosat mobility and autonomy for small bodies exploration, ultra-high-resolution X-ray optics	Selected by NASA Centers
Small Business Innovative Research (SBIR)/ Small Business Technology Transfer (STTR)	1-6	Current solicitation has thirty-one subtopics covering instrument and platform technologies relevant to SMD	Competitive solicitation
Game Changing Development	3-5	SEXTANT, WFIRST-AFTA coronagraph, advanced entry technologies	New starts selected by STMD
Centennial Challenges	3-5	Sample return robot to locate and retrieve geologic samples from a wide and varied terrain without human control	Various challenges
Small Spacecraft Technology	3-7	Propulsion, communication and other platform technologies for CubeSats and smallsats	Competitive solicitation (REDDI)
Flight Opportunities	5-7	Technology demonstration on emerging suborbital launch vehicles	Competitive solicitation (REDDI)
Technology Demonstration Missions	5-7	Laser Communications Relay Demonstration, Deep Space Atomic Clock, Green Propulsion Infusion Mission, Solar Sail Demonstration	Competitive solicitation (REDDI)



TOP: Artist's concept of the Lunar Laser Communications Demonstration (LLCD) aboard the LADEE spacecraft. *Image Credit: NASA*

BOTTOM LEFT: Artist's concept of the Intelligent Payload Experiment (IPEX) and M-Cubed/COVE-2 (CubeSat Onboard processing Validation Experiment-2), two NASA Earth-orbiting cube satellites ("CubeSats") that were launched as part of the NRO Launch-39 GEMSat (Government Experimental Multi-Satellite) mission from California's Vandenberg Air Force Base on Dec. 5, 2013. CubeSats typically have a volume of exactly one liter. *Image Credit: NASA/JPL*

BOTTOM RIGHT: Currently, space clocks utilize Cesium ions to keep their time synchronous with Earth. Drift is a phenomenon that occurs over time where two clocks will no longer display the same time as one another. To avoid drift and to increase the stability of the ion clock, a new atomic element is needed for use in new space clocks. NASA engineers have been studying use of Mercury ions in satellite space clocks to allow engineers on the ground to more precisely navigate spacecraft and control their onboard instruments. *Image Credit: NASA*

4. Industry: Aerospace corporations often invest significant resources on internal research and development of technologies that have the potential to support future science missions.
5. Academia: Much of the early work needed to advance technology is conducted at universities with funds they receive to study future mission concepts.
6. Other international space agencies: The success of many high-profile mission concepts for breakthrough science depends upon collaboration with international partners who might be further along in their technology development for a particular area of science.

SMD also undertakes technology development activities in each science division, as described in chapter 4.

Technology development programs are essential for extending the reach of scientific discovery. The comprehensive approach employed by SMD encompasses both near-term and long-term technology development, partnerships with external organizations, and internal technology development, thus enabling the advancement of technologies necessary for future science missions.



CHAPTER 7

Engaging the **Next**
Generation

LEFT: Life-size model of JWST on display at the 2013 South by Southwest (SXSW) conference in Austin, Texas. *Image Credit: NASA/Jenny Mottar*



Students attending Space Camp at the Space and Rocket Center in Huntsville, AL eagerly ask questions of the deep space exploration panel during the public viewing of the flawless launch of the MAVEN mission to Mars on November 18, 2013. *Image Credit: NASA/MSFC/Emmett Given*

Strategy

SMD's education and public outreach (E/PO) strategy directly contributes to the executive branch's framework to effectively deliver STEM education to more students and teachers across the nation and supports the Agency's education objective articulated in NASA's 2014 strategic plan: "Advance the Nation's STEM education and workforce pipeline by working collaboratively with other agencies to engage students, teachers, and faculty in NASA's missions and unique assets." SMD remains focused on realizing the unique contribution NASA science makes towards meeting the nation's education needs and on enhancing the public's understanding of science. SMD's vision for E/PO is

To share the story, the science, and the adventure of NASA's scientific explorations of our home planet, the solar system, and the universe beyond, through stimulating and informative activities and experiences created

by experts, delivered effectively and efficiently to learners of many backgrounds via proven conduits, thus providing a direct return on the public's investment in NASA's scientific research.

At the same time, SMD must be responsive to national priorities and directives. In May 2013, the NSTC CoSTEM released the *Federal STEM Education 5-Year Strategic Plan*, outlining goals in five priority STEM education investment areas. In response to this plan, SMD will continue to support and collaborate with other agencies in the priority areas identified by the plan:

1. Improve STEM Instruction
2. Increase and Sustain Youth and Public Engagement in STEM

3. Enhance STEM Experience of Undergraduate Students
4. Better Serve Groups Historically Under-represented in STEM Fields
5. Design Graduate Education for Tomorrow's STEM Workforce

Furthermore, the President's FY 2014 budget request proposed a cohesive framework for delivering STEM education to students and teachers effectively. The President's FY 2015 budget request included several changes to the original STEM proposal to ensure a smooth transition to the new framework, incorporating feedback from a wide range of stakeholders on how best to approach STEM education. The FY 2015 budget includes dedicated funding for SMD, which is evidence of the important role that NASA's science program plays in inspiring students, teachers, and the public about science and in particular, STEM careers.

While SMD is still developing policies and processes for implementing a more focused and cohesive portfolio of education programs, the directorate has established several tenets that are consistent with the executive branch's new STEM framework and the NSTC CoSTEM *Federal STEM Education 5-Year Strategic Plan*:

1. SMD will maintain an important role in science education and public engagement for the nation.
2. In cooperation with NASA's Office of Education, SMD will ensure alignment with the CoSTEM goal structure.
3. Existing E/PO activities will be evaluated for effectiveness to determine if they should continue and future E/PO activities will be competed.

NASA's science program is unique among federal agencies. Through competitive selection and strategic partnerships, SMD's E/PO opportunities inspire students, teachers, and the public at large to seek out new science discoveries and to acquire new skills in science, engineering, technology, and mathematics.

Implementation

Ever since it formally established E/PO policies in 1995, SMD has strived to increase science literacy rates for the U.S. population. Consistent with that objective, SMD E/PO



The Global Learning and Observation to Benefit the Environment (GLOBE) program is a worldwide community of students, teachers, scientists and citizens working together to promote the teaching and learning of science, enhance environmental literacy and stewardship, and promote scientific discovery. *Image Credit: NASA/GLOBE*

efforts encompass both science education and workforce development. SMD integrally implements its E/PO efforts primarily through two means. First, it embeds E/PO projects in certain flight programs and missions, which allocate a portion of their mission budgets for E/PO activities. These missions develop E/PO plans during the early phases of the mission lifecycle, and these plans are subjected to thorough review and approval processes similar to those used for mission subsystems. SMD also offers proposal opportunities for E/PO efforts as part of its annual competitive solicitation process. SMD may award solicited or unsolicited E/PO proposals, or fund E/PO efforts as elements of a major research-enabling program (e.g., suborbital science, science instrumentation, data and information systems, etc.). Science mission staff—especially researchers—are particularly encouraged to become active participants in E/PO activities.



Available on iTunes®, YouTube®, and Vimeo®, ScienceCasts are short videos about fun, interesting, and unusual NASA science topics. *Image Credit: NASA*

Science Education

Currently, science experts share the results of NASA missions and research with audiences through a portfolio of education and outreach projects targeted to students in higher education, elementary, and secondary school and the general public. These E/PO efforts are delivered by both paid and volunteer networks, such as the Solar System Ambassadors and Educators and the Night Sky Network. One aim is to attract and retain students in STEM disciplines by energizing science teaching and learning. In addition, E/PO projects promote inclusiveness and provide opportunities for minorities, students with disabilities, students at minority universities, and other target groups to compete for and participate in science missions, research, and education programs.

Collaboration is critical to building and sustaining nationwide programs that contribute to improving teaching and learning at the precollege level and to increasing the scientific literacy of the general public. SMD fosters such collaboration by building on existing programs, institutions, and infrastructure and by coordinating activities and encouraging partnerships with other ongoing education efforts both within and external to NASA. SMD has established informal education alliances with science centers, museums, and planetariums through the NASA Museum Alliance, as well as with public radio and

television program producers. SMD also works to enrich the STEM education efforts of community groups such as the Girl Scouts, 4-H Clubs, and the Boys and Girls Clubs of America. The strength of each of these partnerships relies on the combination of the science content knowledge and expertise of SMD and the educational expertise and context of each partner.

Most educational products created under the auspices of SMD are readily available to the public through www.nasawavelength.org. The resources included in the on-line catalog have all passed the SMD Education Product Review, where resources are reviewed for both content accuracy and pedagogy. In addition, this site provides direct links to other relevant NASA sites, as well as other national databases containing educational materials.

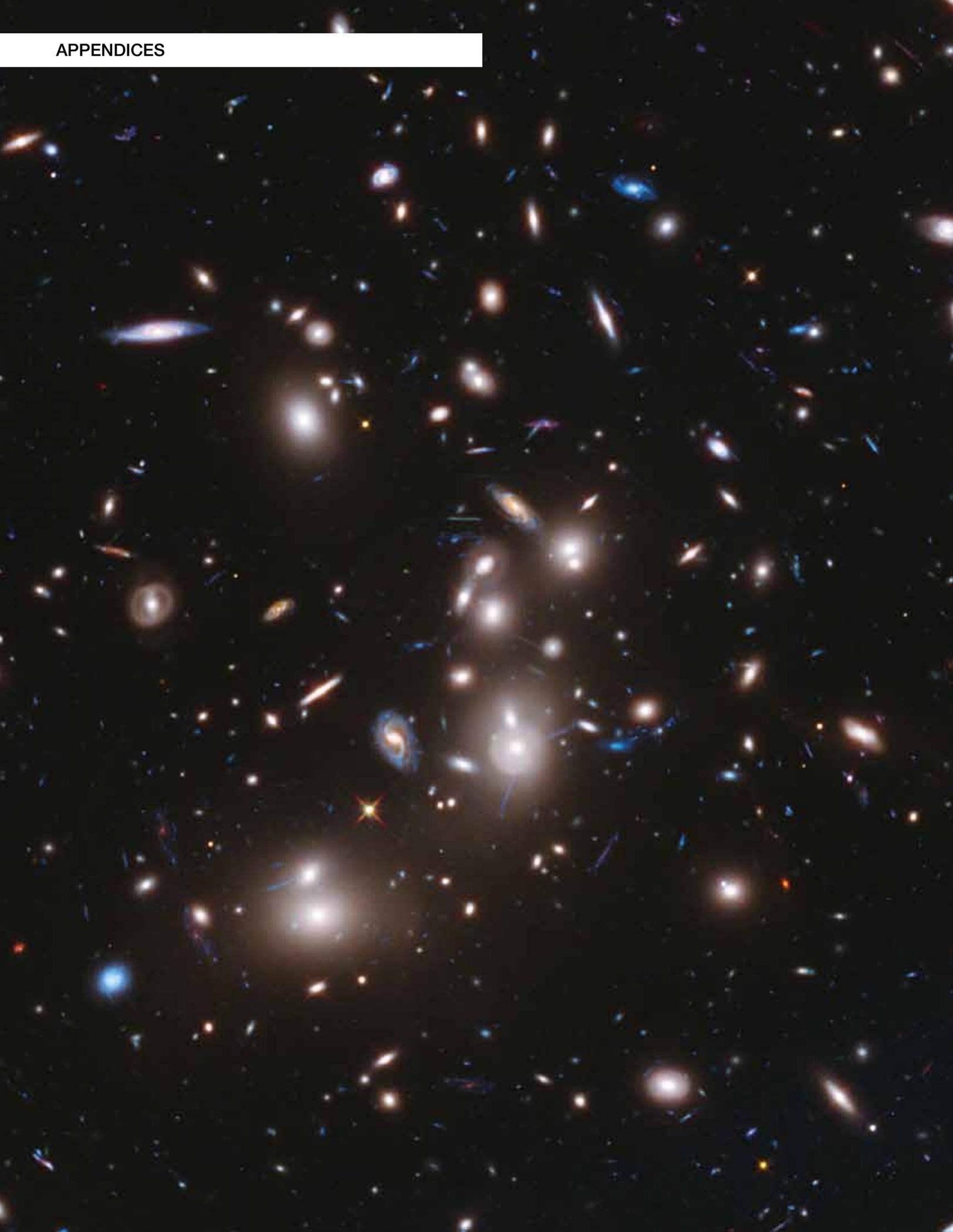
SMD also utilizes independent education experts to evaluate and provide feedback on the quality and impact of all E/PO projects. In 2009, SMD established Science E/PO Forums (SEPOFs) to facilitate NASA collaboration with external science, education, and outreach communities. In 2014, SMD will assess the effectiveness of the SEPOFs to determine if they will be continued as part of the overall SMD E/PO restructuring.

Workforce Development

To prepare America's future workforce, NASA makes many professional development opportunities available that are firmly rooted in the science and technology of NASA science missions. SMD aids in workforce development by supporting students at the undergraduate, graduate, and postdoctoral levels. Students may be embedded in SMD research, technology, or flight projects, or may participate in other distinct educational opportunities. The university-based research and technology projects sponsored by SMD allow students and postdoctoral researchers to gain invaluable NASA science program work experience as part of their educational and professional training. Suborbital programs (airplanes, unmanned aircraft systems, rockets, and balloons) and PI-led missions enable students to participate in the entire lifecycle of a science mission, from design and construction, to flight and data analysis. These hands-on opportunities provide students with experiences in problem solving and enable increased understanding of the systems engineering concepts that are the underpinning of successful science missions. In addition, the Student Airborne Research Program offers advanced undergraduate students hands-on research experience in all aspects of a major scientific campaign. Furthermore, the NASA Post-doctoral Program, NASA Earth and Space Science Fellowship Program, and other early-career programs (e.g., Early Career Fellowships, New Investigator Program in Earth Science) ensure the continued training and nurturing of a highly qualified workforce to help NASA continue the scientific exploration of Earth and space. SMD also supports the Presidential Early Career Awards for Scientists and Engineers, led by the Office of Science and Technology Policy.



Science On a Sphere® is a room-sized, global display system that uses computers and video projectors to display planetary data onto a six foot diameter sphere, analogous to a giant animated globe. *Image credit: NASA*



Appendices

LEFT: This long-exposure Hubble Space Telescope image of massive galaxy cluster Abell 2744 is the deepest ever made of any cluster of galaxies. It shows some of the faintest and youngest galaxies ever detected in space. The immense gravity in Abell 2744 acts as a gravitational lens to warp space and brighten and magnify images of nearly 3,000 distant background galaxies—some that formed more than 12 billion years ago, not long after the big bang. *Image Credit: NASA/STScI*

Appendix A: Status of NRC Decadal Survey Recommendations and/or National Priorities**HELIOPHYSICS**

Program/Mission Concept	Class*	Recommendation	Status
Heliophysics Explorer Program		Accelerate and expand program	Next AO NET 2016
Ionospheric Connection (ICON)	Small	Complete missions in development	In formulation. Launch Readiness Date (LRD): 2017
Global-scale Observations of the Limb and Disk (GOLD)	Small	Complete missions in development	In formulation. LRD: 2017
Solar Terrestrial Probes Program		Restructure as higher cadence medium PI-led program	STP-5 LRD: NET 2023
Magnetospheric Multiscale (MMS)	Large	Complete missions in development	In development. LRD: 2015
Living With a Star Program		Start next LWS mission by end of the decade	Next LWS AO post 2020
Space Environment Testbeds (SET-1)	Small	Complete missions in development	In development. LRD: 2016
Solar Orbiter Collaboration (SOC)	Medium	Complete missions in development	In development. LRD: NLT 2018 [^]
Solar Probe Plus (SPP)	Large	Complete missions in development	In development. LRD: 2018

* As determined by the 2013 Heliophysics decadal survey, which defines mission class as follows: Small (Explorer Class) - \$50M-\$300M; Medium - \$300M-\$600M; and Large - >\$600M

[^] Reflects the Agency baseline commitment to launch NLT the year identified.

EARTH SCIENCE

Program/Mission Concept	Class	Recommendation	Status
Earth Systematic Missions Program			
Global Precipitation Measurement (GPM)	FM (DS-2007)	Launch GPM by 2012 (DS-2007)	Launched February 27, 2014
Soil Moisture Active-Passive (SMAP)	Tier 1 Mission	Complete missions in development	In development LRD: NLT 2015 [^]
	CCAP	LRD: 2014	
Stratospheric Aerosol and Gas Experiment III (SAGE III)	CCAP	LRD: 2013	In development LRD: NLT 2016 [^]
Ice, Cloud and land Elevation Satellite – 2	Tier 1 Mission (DS-2007)	Launch: 2010-13	In development. LRD: Under review
Gravity Recovery and Climate Experiment Follow-on (GRACE FO)	CCAP	LRD: 2016	In formulation. LRD: NLT 2018 [^]
Surface Water and Ocean Topography (SWOT)	Tier 2 Mission (DS-2007)	Launch: 2013-16	In Formulation. LRD: 2020

EARTH SCIENCE (Continued)

Program/Mission Concept	Class	Recommendation	Status
Earth Systematic Missions Program (Continued)			
Sustained Solar Irradiance Measurements	National Priority	Responsibility transferred from NOAA to NASA	Instrument Opportunity. LRD: NET 2020
Pre-Aerosol, Cloud, ocean Ecosystem (PACE)	CCAP	LRD: 2018	In formulation. LRD: NET 2020
L-Band Synthetic Aperture Radar	Tier 1 Mission	Launch: 2010-13	In formulation. Being studied as a partnership with India. LRD: 2021
	CCAP	LRD: 2017	
Vertical Ozone Profiles	National Priority	Responsibility transferred from NOAA to NASA	Instrument on JPSS-2. LRD: NET 2021
Earth's Radiation Budget	National Priority	Responsibility transferred from NOAA to NASA	Instrument on JPSS-2. LRD: NET 2021
Climate Absolute Radiance and Refractivity Observatory (CLARREO)	Tier 1 Mission (DS-2007)	Launch: 2010-13	In formulation LRD: NET 2023
	CCAP	LRD: 2017	
Active Sensing of CO2 Emissions Over Nights, Days, and Seasons (ASCENDS)	Tier 2 Mission (DS-2007)	Launch: 2013-16	In formulation LRD: TBD
	CCAP	LRD: 2019	
Geostationary Coastal and Air Pollution Events (GEO-CAPE)	Tier 2 Mission (DS-2007)	Launch: 2013-16	In formulation LRD: TBD
Hyperspectral Infrared Imager (HyspIRI)	Tier 2 Mission (DS-2007)	Launch: 2013-16	In formulation LRD: TBD
Aerosol-Clouds-Ecosystems	Tier 2 Mission (DS-2007)	Launch: 2013-16	In formulation LRD: TBD
Precipitation and All-weather Temperature and Humidity (PATH)	Tier 3 Mission (DS-2007)	Launch: 2016-20	In formulation LRD: TBD
Snow and Cold Land Processes (SCLP)	Tier 3 Mission (DS-2007)	Launch: 2016-20	In formulation LRD: TBD
Global Atmospheric Composition Mission (GACM)	Tier 3 Mission (DS-2007)	Launch: 2016-20	In formulation LRD: TBD
Three-Dimensional Tropospheric Winds (3D-Winds) (demo)	Tier 3 Mission (DS-2007)	Launch: 2016-20	In formulation LRD: TBD
Lidar Surface Topography (LIST)	Tier 3 Mission (DS-2007)	Launch: 2016-20	In formulation LRD: TBD
Gravity Recovery and Climate Experiment-II (GRACE-II)	Tier 3 Mission (DS-2007)	Launch: 2016-20	In formulation LRD: TBD
Future Land Imaging	National Priority	Establish a sustained land imaging capability for the nation	Under study with USGS

APPENDICES

EARTH SCIENCE (Continued)

Program/Mission Concept	Class	Recommendation	Status
Earth System Science Pathfinder Program			
Orbiting Carbon Observatory-2 (OCO-2)	CCAP		In development. LRD: NLT 2015 [^]
Earth Venture Mission (EVM)	Earth Venture (DS-2007)	Initiate frequent, low-cost, innovative research and application missions	EVM-1: Cyclone Global Navigation Satellite System (CYGNSS) LRD: NLT 2017 [^] EVM-2: Solicitation for 2 in 2015 and at 4-year intervals
	CCAP	EVM-2 LRD: 2017	
Earth Venture Instrument (EVI)	Earth Venture (DS-2007)	Initiate frequent, low-cost, innovative research and application missions	EVI-1: Tropospheric Emissions: Monitoring of Pollution (TEMPO) LRD: 2018 EVI-2: Solicitation in 2013 and at 18-month intervals
Earth Venture Suborbital (EVS)	Earth Venture (DS-2007)	Initiate frequent, low-cost, innovative research and application missions	EVS-1: 5 investigations selected in 2010; multiple field campaigns through 2015. EVS-2: Solicitation in 2013 and at 4-year intervals
Earth Science Research Program			
Suborbital Program	Program Element (DS-2007)	Augment funding for suborbital program	NRC Midterm Assessment (2012): The suborbital program, and in particular the Airborne Science Program, is highly synergistic with upcoming Earth science satellite missions and is being well implemented. NASA has fulfilled the recommendation of the decadal survey to enhance the program.

FM: Foundation Mission

DS: Decadal Survey

CCAP: NASA's 2010 Climate-centric Architecture Plan

[^] Reflects the Agency baseline commitment to launch NLT the year identified.

PLANETARY SCIENCE

Program/Mission Concept	Class*	Recommendation	Status
The Discovery Program		Continue program with 2yr cadence on mission AOs	Next Discovery AO in FY14; planning a 3 year cadence for future calls
InSight	Small		In development. LRD: NLT 2016 [^]
New Frontiers Program		7 candidate missions with 2 selected before 2022	Next AO TBD
Origins Spectral Interpretation, Resource Identification and Security Regolith Explorer (OSIRIS-REx)	Medium		In development. LRD: NLT 2016 [^]
Mars Exploration Program			
ExoMars Trace Gas Orbiter (ESA)	N/A		Providing Electra telecommunication radios. In development: LRD: 2016

PLANETARY SCIENCE (Continued)

Program/Mission Concept	Class*	Recommendation	Status
Mars Exploration Program (Continued)			
ExoMars Rover (ESA)	N/A		Providing MOMA-MS instrument. In formulation. LRD: 2018
Mars Astrobiology Explorer-Cacher (MAX-C)	Large	1st priority flagship mission launched before 2022 @ \$2B in FY15 dollars	Mars 2020 rover in formulation. LRD: 2020
Strategic Missions			
Jupiter Icy Moons Explorer (JUICE) (ESA)	N/A		Providing UV Imaging Spectrograph. LRD: 2022
Jupiter Europa Orbiter	Large	2nd priority flagship mission to be launched before 2022	NASA is evaluating a variety of options for a potential Europa mission, including options that cost less than \$1 billion. LRD: TBD
Uranus Orbiter and Probe	Large	3rd priority flagship mission to be launched before 2022	No active study underway
Enceladus Orbiter	Large	4th priority flagship mission to be launched before 2022	No active study underway
Venus Climate Orbiter	Large	5th priority flagship mission to be launched before 2022	No active study underway

* As determined by the 2011 Planetary Science decadal survey, which defines mission class as follows: Small - <\$450M; Medium - \$450M-\$900M; and Large - >\$900M.

^ Reflects the Agency baseline commitment to launch NLT the year identified.

ASTROPHYSICS

Program/Mission Concept	Class*	Recommendation	Status
Physics of the Cosmos Program			
Laser Interferometer Space Antenna (LISA) Pathfinder	Medium		ESA-led mission with NASA participation. LRD: 2015
Euclid	Medium		ESA-led mission with NASA participation. LRD: 2020
Laser Interferometer Space Antenna (LISA)	Large	Also recommended in 2001 decadal survey	Potential partnership with ESA for the L3 gravitational wave mission
International X-ray Observatory (IXO)	Large	4th priority for this mission class	Partnership with ESA for the L2 X-ray observatory mission. LRD: 2028
Cosmic Origins Program			
James Webb Space Telescope (JWST)	Large	Top priority in 2001 decadal survey	Instruments and mirrors complete. Observatory integration and testing on schedule. LRD: NLT 2018^

APPENDICES

ASTROPHYSICS (Continued)

Program/Mission Concept	Class*	Recommendation	Status
Exoplanet Exploration Program			
Wide Field Infrared Survey Telescope (WFIRST)	Large	Top priority for large scale mission in 2010 decadal survey	Under study.
Astrophysics Explorers Program		Augment current plans to two medium explorers, two small explorers and four MoOs.	Planned cadence supports NRC recommendation
ASTRO-H	Small		JAXA-led mission with NASA participation. LRD: NLT 2016 [^]
Neutron star Interior Composition Explorer (NICER) – 2016	Medium	- -	In formulation. LRD: NLT 2017 [^]
Transiting Exoplanet Survey Satellite (TESS)	Medium	- -	In formulation: LRD: 2018
Space Infrared Telescope for Cosmology and Astrophysics (SPICA) Mission (Japan)	Small	Contribution to Japanese mission	Candidate for future Explorer MoO.
Astrophysics Research Program			
Suborbital Program	Small	Augmentation	Technology augmentation for balloon program. Continuing development of Ultra Long Duration Balloon (ULDB) platforms. Potential ISS payload opportunities.
New Worlds Technology Development Program	N/A	New program to support post 2020 planet imaging mission	Advancing technology through SAT and APRA and in partnership with STMD. Potential demonstration instrument on WFIRST.
Inflation Probe Technology Development Program	N/A	New program to support post-2020 cosmic microwave background inflation mission	Technology development and suborbital projects supported through SAT and APRA

* As determined by the 2010 Astrophysics decadal survey, which defines mission class as follows: Small - <\$300M; Medium - \$300M-\$1B; and Large - >\$1B.

[^] Reflects the Agency baseline commitment to launch NLT the year identified.

Appendix B: NASA Strategic Goals and Objectives, SMD Division Science Goals, Decadal Survey Priorities, and SMD Missions

NASA Strategic Objective	SMD Division Science Goals	Decadal Survey Priority (Associated SMD Division Science Goals in parentheses)	SMD Missions (Associated Decadal Survey Priorities in parentheses)	
NASA Strategic Goal: Expand the frontiers of knowledge, capability, and opportunity in space.				
<p>HELIOPHYSICS</p> <p>Understand the Sun and its interactions with Earth and the solar system, including space weather.</p>	<ol style="list-style-type: none"> 1. Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system. 2. Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system. 3. Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth. 	<ol style="list-style-type: none"> a. Determine the origins of the Sun's activity and predict the variations of the space environment. (1, 3) b. Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. (2, 3) c. Determine the interaction of the Sun with the solar system and the interstellar medium. (1, 2) d. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe. (1, 2) 	<p>ACE (a, c, d) AIM (b) ARTEMIS (d) CINDI (b) Cluster-ESA (d) Geotail-JAXA GOLD (b) Hinode (Solar B)-JAXA (a, d) IBEX (a, c) ICON (b) IRIS (a, d) MMS (b, d) RHESI (a, d)</p>	<p>SDO (a, d) SOHO-ESA (a, c, d) SOC-ESA (a, c, d) Solar Probe Plus (a, c, d) STEREO (a, c, d) THEMIS (d) TIMED (b) TWINS (b) Van Allen Probes (d) Voyager (a, c, d) Wind (a, c, d)</p>
<p>PLANETARY SCIENCE</p> <p>Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere.</p>	<ol style="list-style-type: none"> 1. Explore and observe the objects in the solar system to understand how they formed and evolve. 2. Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve. 3. Explore and find locations where life could have existed or could exist today. 4. Improve our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere. 5. Identify and characterize objects in the solar system that pose threats to Earth, or offer resources for human exploration. 	<ol style="list-style-type: none"> a. Building New Worlds—advance the understanding of solar system beginnings (1, 2) b. Planetary Habitats—search for the requirements for life (3, 4) c. Workings of Solar Systems—reveal planetary processes through time (1, 2, 5) 	<p>MESSENGER (a, c) BepiColumbo (a, c) Venus Express (a, b, c) Venus Climate Orbiter (a, b, c) LADEE (a, c) LRO (a, c) Hayabusa 2 (a, c) Rosetta (a, c) OSIRIS-REx (a, c) Odyssey (a, b, c) MRO (a, b, c) MAVEN (c)</p>	<p>Opportunity (a, b, c) Curiosity (a, b, c) Mars Rover 2020 (a, b, c) ExoMars 2016 (c) ExoMars 2018 (a, b, c) Mars Express (c) Dawn (a, c) Juno (a, c) JUICE (a, b, c) Cassini (a, b, c) New Horizons (a, c)</p>

Appendix B (Continued): NASA Strategic Goals and Objectives, SMD Division Science Goals, Decadal Survey Priorities, and SMD Missions

NASA Strategic Objective	SMD Division Science Goals	Decadal Survey Priority (Associated SMD Division Science Goals in parentheses)	SMD Missions (Associated Decadal Survey Priorities in parentheses)	
NASA Strategic Goal (Continued): Expand the frontiers of knowledge, capability, and opportunity in space.				
<p>ASTROPHYSICS</p> <p>Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.</p>	<ol style="list-style-type: none"> 1. Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity. 2. Explore the origin and evolution of the galaxies, stars and planets that make up our universe. 3. Discover and study planets around other stars, and explore whether they could harbor life. 	<ol style="list-style-type: none"> a. Search for the first stars, galaxies, and black holes (1, 2) b. Seek nearby habitable planets (3) c. Advance understanding of the fundamental physics of the universe (1, 2) 	<p>ASTRO-H-JAXA (c) Chandra (a, c) Euclid-ESA (b, c) Fermi (a, c) Hubble (a, b, c) JWST (a, b, c) Kepler (b) LISA Pathfinder-ESA (c) NICER (c)</p>	<p>NuSTAR (a, c) SOFIA[^] (a, b) Spitzer (a, b) Suzaku-JAXA (c) Swift (a, c) TESS (b) XMM-Newton-ESA (a, c)</p>
NASA Strategic Goal: Advance understanding of Earth and develop technologies to improve the quality of life on our home planet				
<p>EARTH SCIENCE</p> <p>Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet.</p>	<ol style="list-style-type: none"> 1. Advance the understanding of changes in the Earth's radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition. 2. Improve the capability to predict weather and extreme weather events. 3. Detect and predict changes in Earth's ecosystems and biogeochemical cycles, including land cover, biodiversity, and the global carbon cycle. 4. Enable better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change. 5. Improve the ability to predict climate changes by better understanding the roles and interactions of the ocean, atmosphere, land and ice in the climate system. 6. Characterize the dynamics of Earth's surface and interior, improving the capability to assess and respond to natural hazards and extreme events. 7. Further the use of Earth system science research to inform decisions and provide benefits to society. 	<ol style="list-style-type: none"> a. Understand the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future. (3, 5, 6, 7) b. Revitalize the nation's research satellite system, providing near-term measurements to advance science, underpin policy, and expand applications and societal benefits* (5) c. Advance climate research, multiply applications using the full set of available (NASA and non-NASA) satellite measurements for direct societal benefit, and develop/mature technologies required for the next generations of Earth observing missions* (1, 2, 4) <p>* NASA's 2010 climate-centric architecture plan</p>	<p>AirMOSS (c) Aqua (a, c) Aquarius (a, c) ATTREX (a) Aura (a, c) CALIPSO (a, c) CARVE (a) CloudSat (a, c) CYGNSS (b) DISCOVER-AQ (b) EO-1 (b) GPM (a, c) GRACE (a, c) GRACE FO (a, c) HS-3 (a) ICESat-2 (a, b, c) IIP (c) Landsat-8 (a, b, c)</p>	<p>OCO-2 (a, c) Operation IceBridge (a, c) OSTM/Jason 2 (a, c) QuikSCAT (a, c) SAGE III (a, b, c) SMAP (a, b, c) SORCE (a, c) Suomi NPP (b) SWOT (a, c) TEMPO (a, b) Terra (a, c) TRMM (a, c)</p>

[^] The FY15 Budget greatly reduces funding for SOFIA

Appendix C: Program/Strategic Mission Lines

Program/Strategic Mission Lines	Category*	Objectives and Features	Example Missions
Earth Systematic Missions	Strategic missions (Category 1, 2, 3)	Make new global measurements to address unanswered questions and reduce remaining uncertainties; maintain continuity of key measurements awaiting transition to operational systems managed by other agencies.	GPM, SMAP, ICESat-2, decadal survey missions
Earth System Science Pathfinder (ESSP)	Competed, PI-led missions (Category 3)	Address focused Earth science objectives and provide opportunities for new science investigations. Includes the Venture class of suborbital campaigns, small satellites, and instruments of opportunity.	TEMPO, CYGNSS
Discovery	Competed, PI-led missions (Category 2, 3)	Regular, lower cost, highly focused planetary science investigations of any solar system bodies other than the Earth and Sun.	Dawn, MESSENGER, InSight
New Frontiers	Competed, PI-led missions (Category 1, 2)	Focused scientific investigations designed to enhance our understanding of the solar system; competitively selected from among a specified list of candidate missions/science targets.	New Horizons, Juno, OSIRIS-REx
Mars Exploration	Strategic missions (Category 1, 2)	Maximize the scientific return, technology infusion, and public engagement of the robotic exploration of the Red Planet. Each strategic mission has linkages to previous missions, and orbiters and landers support each other's operations.	Curiosity, MRO, Mars 2020
Solar Terrestrial Probes (STP)	Strategic missions (Category 1,2)	Strategic sequence of missions to provide understanding of the fundamental plasma processes inherent in all astrophysical systems.	TIMED, Hinode (Solar B), STEREO, MMS
Living With a Star (LWS)	Strategic missions (Category 1, 2)	Strategic missions targeted toward those aspects of the Sun and space environment that most directly affect life and society.	SDO, Van Allen Probes, SOC, Solar Probe Plus
Heliophysics Explorers	Competed, PI-led missions (Category 2, 3)	Provide flight opportunities for focused scientific investigations from space in Heliophysics	IRIS, ICON, GOLD
Cosmic Origins	Strategic missions (Category 1, 2, 3)	Strategic missions to understand how the familiar universe of stars, galaxies, and planets are formed over time	JWST, Hubble, Spitzer, SOFIA [^]
Physics of the Cosmos	Strategic missions (Category 1, 2, 3)	Strategic missions to explore fundamental questions regarding the physical forces and laws of the universe including the nature of spacetime, the behavior of matter and energy in extreme environments, the cosmological parameters governing inflation and the evolution of the universe, and the nature of dark matter and dark energy	Chandra, Fermi, Euclid, XMM-Newton, LISA-Pathfinder
Exoplanet Exploration	Strategic missions (Category 1, 2, 3)	Strategic missions to explore and characterize new worlds, enable advanced telescope searches for Earth-like planets, and discover habitable environments around neighboring stars	Kepler
Astrophysics Explorers	Competed, PI-led missions (Category 2, 3)	Provide flight opportunities for focused scientific investigations from space in Astrophysics	NuSTAR, TESS, ASTRO-H, NICER, Swift, Suzaku

* Category 1: > \$1B; Category 2: \$250M - \$1B; Category 3: < \$250M

[^] The FY15 Budget greatly reduces funding for SOFIA

Appendix D: Science Directorate Decision-Making Process for Missions

Mission Lifecycle Phase	Description
Spaceflight Mission Initiation	<p>SMD spaceflight missions are initiated by one of two processes:</p> <ol style="list-style-type: none"> 1. Strategic missions for SMD are initially developed as candidates from multiple mission investigation concepts that derive from various surveys and studies performed by science advisory boards and panels, or that meet specific Agency Science goals. 2. Competed missions are those selected through open AOs, which solicit a scientific investigation that includes development of a flight mission or instruments to fly on currently planned flight missions or platforms such as the ISS. <p>All proposed missions must fit within a Science Mission Directorate goal or specific objective. Division Directors then package related missions into appropriate programs for further management consideration.</p>
Pre-formulation*	<p>The NASA Headquarters Science Management Council (SMAc) reviews candidate science programs and makes appropriate recommendations to the SMD AA who approves new initiatives for further study.</p> <p>Approved mission initiatives must clear Key Decision Points (KDPs) to determine readiness before they are allowed to proceed to the next mission lifecycle phase. Missions that do not clear a KDP are either given more time to achieve readiness or considered for termination.</p>
Phase-A (Formulation)	<p>Phase A of Formulation defines mission and system concepts, parameters, constraints, and requirements that will allow the project to be developed on a schedule that meets established goals and can be achieved for a realistic cost. This is done by conducting studies that examine the mission characteristics permitted within identified constraints, and through continued development of enabling technology toward achieving an acceptable TRL. A prime focus is to identify the top-level requirements that the mission must satisfy in order to meet science objectives. The transition to Phase B involves independent review and approvals at multiple levels, culminating in the KDP-B meeting to ensure that the project is ready to proceed from Phase A to Phase B.</p>
Phase-B (Formulation)	<p>Phase B of Formulation concentrates on applying results of mission studies and trades completed in Phase A to generate preliminary mission, instrument, and spacecraft designs that satisfy the identified constraints and requirements, and that will allow the project to be developed on a schedule to meet established goals within budget. A descscope plan must be prepared to pursue scope reduction and risk management to control cost. It is a time to finalize the requirements and establish the cost caps that will become firm requirements in the Decision Memoranda signed at KDP-C.</p>
Phase-C (Final Design and Fabrication)	<p>Phase C comprises final mission design and fabrication. While there are no strategic decisions during this stage, the SMD AA has a vested interest in ensuring that mission implementing organizations carry out assigned tasks effectively, tracking the performance of a project against the program-level requirements and against the schedule and cost cap.</p>
Phase-D (Integration, Test, Launch)	<p>Phase D includes integration, test and launch. Phase D begins after final assembly of the deliverable system (whether a spacecraft or an instrument) commences. It also includes system-level environmental testing, delivery to the launch site for launch processing, launch operations, and on-orbit checkout. The transition of a flight project from Phase D to Phase E occurs only after on-orbit checkout has been completed, typically 30 to 90 days after launch.</p>
Phase-E (Operations)	<p>Phase E comprises operation of the prime or planned mission. At the end of the prime mission, an End of Prime Mission (EOPM) review is held to (1) evaluate and document how the mission achieved its Level 1 science requirements and mission success criteria, and (2) identify lessons learned based on the actual operations that can be used to improve future missions. It is not considered a gate review, but the EOPM results are considered when inviting the mission to propose for an extended mission.</p>
Mission Cancellation (Pre-Launch)	<p>The project will implement a mission within the established cost and schedule baseline. If a mission is expected to exceed its baseline cost and schedule commitments, it can be considered for cancellation by NASA.</p>
Mission Termination	<p>Missions that continue functioning near the end of their prime operational mission, and any previously extended mission are subject to a Senior Review, which is a science peer review process conducted every two years to determine the scientific value and priority of further mission extensions. Those that do not receive a positive outcome for continuation are subject to termination.</p>

* Strategic missions require approval from the NASA Administrator, the Office of Management and Budget, and Congress. Approval by the SMD AA of missions originating from a Program line like Explorers or Discovery is subject to the availability of funds.

Appendix E: References

NASA Documents

- National Aeronautics and Space Administration. *2010 Science Plan for NASA's Science Mission Directorate*. Washington, DC: NASA Headquarters, 2010. Retrieved from <http://science.nasa.gov/media/medialibrary/2010/08/10/2010SciencePlan.pdf>
- . *NASA Strategic Plan 2014*. Washington, DC: NASA Headquarters, 2014. Retrieved from <http://www.nasa.gov/news/budget/index.html>
- . *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space*. Washington, DC: NASA Headquarters, 2010. Retrieved from http://science.nasa.gov/media/medialibrary/2010/07/01/Climate_Architecture_Final.pdf
- National Aeronautics and Space Administration, Office of the Chief Engineer. *NASA Procedural Requirement 7120.5e: NASA Space Flight Program and Project Management Requirements*. 2012. Retrieved from <http://nodis3.gsfc.nasa.gov>
- National Aeronautics and Space Administration, Science Mission Directorate, Astrophysics Division. *Astrophysics Implementation Plan*. Washington, DC: NASA Headquarters, 2012. Retrieved from <http://science.nasa.gov/astrophysics/documents>
- National Aeronautics and Space Administration Advisory Council Science Committee, Astrophysics Subcommittee. *Enduring Quests, Daring Visions; NASA Astrophysics in the Next Three Decades*. Washington, DC: NASA Headquarters, 2013. Retrieved from <http://science.nasa.gov/astrophysics/documents>
- National Aeronautics and Space Administration Advisory Council Science Committee, Heliophysics Subcommittee. *Our Dynamic Space Environment: Heliophysics Science and Technology Roadmap for 2014-2033*. Washington, DC: NASA Headquarters, 2014. Retrieved from <http://science.nasa.gov/heliophysics>

NRC Decadal Surveys

- National Research Council. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: The National Academies Press, 2007. Retrieved from http://www.nap.edu/catalog.php?record_id=11820
- . *New Worlds, New Horizons in Astronomy and Astrophysics*. Washington, DC: The National Academies Press, 2010. Retrieved from http://www.nap.edu/catalog.php?record_id=12951
- . *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, DC: The National Academies Press, 2011. Retrieved from http://www.nap.edu/catalog.php?record_id=13117
- . *Solar and Space Physics: A Science for a Technological Society*. Washington, DC: The National Academies Press, 2013. Retrieved from http://www.nap.edu/catalog.php?record_id=13060

Additional NRC documents

- National Research Council. *An Enabling Foundation for NASA's Space and Earth Science Missions*. Washington, DC: The National Academies Press, 2010. Retrieved from http://www.nap.edu/catalog.php?record_id=12822
- . *Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce*. Washington, DC: The National Academies Press, 2010. Retrieved from http://www.nap.edu/catalog.php?record_id=12862
- . *Controlling Cost Growth of NASA Earth and Space Science Missions*. Washington, DC: The National Academies Press, 2010. Retrieved from http://www.nap.edu/catalog.php?record_id=12946
- . *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*. Washington, DC: The National Academies Press, 2011. Retrieved from http://www.nap.edu/catalog.php?record_id=13042
- . *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey*. Washington, DC: The National Academies Press, 2012. Retrieved from http://www.nap.edu/catalog.php?record_id=13405

Additional Documents

- Entekhabi, D., G.R. Asrar, A.K. Betts, K.J. Beven, R.L. Bras, C.J. Duffy, T. Dunne, R.D. Koster, D.P. Lettenmaier, D.B. McLaughlin, W.J. Shuttleworth, M.T. van Genuchten, M.-Y. Wei, and E. F. Wood. An agenda for land-surface hydrology research and a call for the second International Hydrological Decade. *Bull. Am. Meteorol. Soc.*, 80 (10): 2043-2058. 1999. doi: [http://dx.doi.org/10.1175/1520-0477\(1999\)080<2043:AAFSSH>2.0.CO;2](http://dx.doi.org/10.1175/1520-0477(1999)080<2043:AAFSSH>2.0.CO;2)
- Executive Office of the President. *National Space Policy of the United States of America*. 2010. Retrieved from http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf
- Executive Office of the President, National Science and Technology Council, Committee on STEM Education. *Federal Science, Technology, Engineering, and Mathematics (STEM) Education 5-Year Strategic Plan*. 2013. Retrieved from http://www.whitehouse.gov/sites/default/files/microsites/ostp/stem_stratplan_2013.pdf
- Leese, J., T. Jackson, A. Pitman, and P. Dirmeyer. Meeting summary: GEWEX/BAHC International Workshop on Soil Moisture Monitoring, Analysis, and Prediction for Hydrometeorological and Hydroclimatological Applications. *Bull. Amer. Meteor. Soc.*, 82, 1423–1430. 2001. doi: [http://dx.doi.org/10.1175/1520-0477\(2001\)082<1423:MSGBIW>2.3.CO;2](http://dx.doi.org/10.1175/1520-0477(2001)082<1423:MSGBIW>2.3.CO;2)
- United Nations, United Nations Environment Programme. *The Montreal Protocol on Substances that Deplete the Ozone Layer*. 2007. Retrieved from http://ozone.unep.org/new_site/en/montreal_protocol.php
- U.S. Government Accountability Office (GAO). *HIGH-RISK SERIES: An Update* (GAO-13-283). 2013. Retrieved from <http://www.gao.gov/products/GAO-13-283>

APPENDICES

Appendix E (Continued): References

NASA Websites

Airborne Science Program: <https://airbornescience.nasa.gov>

Earth Observing System Data and Information System (EOSDIS): <http://earthdata.nasa.gov>

NASA Advisory Council Science Subcommittees: <http://science.nasa.gov/about-us/NAC-subcommittees>

NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES): <http://nspires.nasaprs.com/external>

National Space Weather Program: <http://www.nswp.gov>

Resources for Earth and Space Science Education: www.nasawavelength.org

Science Mission Directorate: <http://science.nasa.gov>

Service and Advice for Research and Analysis (SARA): <http://science.nasa.gov/researchers/sara>

Appendix F: Acronyms and Abbreviations

Abbreviations and Acronyms	Definition
AA	Associate Administrator
AAAC	Astronomy and Astrophysics Advisory Committee
ACE	Advanced Composition Explorer
ACT	Advanced Component Technology
AFTA	Astrophysics Focused Telescope Assets
AIM	Aeronomy of Ice in the Mesosphere
AIST	Advanced Information Systems Technologies
AMSU-A	Advanced Microwave Sounding Unit-A
AO	Announcement of Opportunity
APRA	Astrophysics Research and Analysis
ARSET	Applied Remote SEnSing Training
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun probes
ASAG	Applied Sciences Advisory Group
ASCENDS	Active Sensing of CO ₂ over Nights, Days and Seasons
ATI	Advanced Technology Initiatives
ATTREX	Airborne Tropical Tropopause Experiment
AU	Astronomical Unit
AVHRR	Advanced Very High Resolution Radiometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
CASI	Climate Adaptation Science Investigators
CATS	Cloud-Aerosol Transport System
CBP	Capacity Building Program
CCAP	NASA's 2010 Climate-Centric Architecture Plan
CCMC	Community Coordinated Modeling Center
CENRS	Committee on Environment, Natural Resources, and Sustainability
CERES	Cloud and the Earth's Radiant Energy System
CIF	Center Innovation Fund
CINDI	Coupled Ion-Neutral Dynamics Investigations
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CNES	Centre National d'Etudes Spatiale (French Space Agency)
CO ₂	Carbon dioxide
CoSTEM	Committee on Science Technology, Engineering and Math Education
COVE-2	CubeSat Onboard processing Validation Experiment-2

Abbreviations and Acronyms	Definition
CRaTER	LRO Cosmic Ray Telescope for the Effects of Radiation instrument
CREAM	Cosmic Ray Energetics and Mass
CSA	Canadian Space Agency
CSLI	CubeSat Launch Initiative
CYGNSS	Cyclone Global Navigation Satellite System
DAAC	Distributed Active Archive Centers
DISCOVER-AQ	Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality
DLR	Deutsches Zentrum für Luft- und Raumfahrt (national aeronautics and space research center of the Federal Republic of Germany)
DOD	Department of Defense
DOE	Department of Energy
DRIVE	Diversify, Realize, Integrate, Venture, Educate
DS	Decadal Survey
DSCOVR	Deep Space Climate Observatory
DWSS	Defense Weather Satellite System
E/PO	Education and Public Outreach
EAR	Export Administration Regulations
EDLS	Entry, Descent, Landing System
ELV	Expendable Launch Vehicle
EM	Exploration Mission
EO-1	Earth Observing-1
EOPM	End of Prime Mission
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
EPA	Environmental Protection Agency
ESA	European Space Agency
ESD	Earth Science Division
ESM	Earth Systematic Missions
ESSP	Earth System Science Pathfinder
ESTO	Earth Science Technology Office
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EVI	Earth Venture—Instrument
EVM	Earth Venture – Mission

APPENDICES

Abbreviations and Acronyms	Definition
EVS	Earth Venture – Suborbital
FAA	Federal Aviation Administration
FY	Fiscal Year
GACM	Global Atmospheric Composition Mission
GAO	Government Accountability Office
GCIS	Global Change Information System
GCOM-W1	Global Change Observation Mission—Water satellite (JAXA)
GEMS	Gravity and Extreme Magnetism Small Explorer
GEO	Geostationary Orbit
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GEOS	Goddard Earth Observing System
GLOBE	Global Learning and Observation to Benefit the Environment
GOES	Geostationary Operational Environmental Satellite
GOLD	Global-scale Observations of the Limb and Disk
GOMI	Gulf of Mexico Initiative
GEMSat	Government Experimental Multi-Satellite
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRACE FO	Gravity Recovery and Climate Experiment Follow-on
GRAIL	Gravity Recovery and Interior Laboratory
GRB	Gamma-ray burst
HEOMD	Human Exploration and Operations Mission Directorate (NASA)
H-GCR	Heliophysics-Grand Challenges Research
H-GI	Heliophysics-Guest Investigator
HICO	Hyperspectral Imager for the Coastal Ocean
HS3	Hurricane and Severe Storm Sentinel
HSO	Heliophysics System Observatory
HST	Hubble Space Telescope
H-TIDeS	Heliophysics Technology and Instrument Development for Science
IBEX	Interstellar Boundary Explorer
ICESat-2	Ice, Clouds and land Elevation Satellite-2
ICON	Ionospheric Connection
IIP	Instrument Incubator Program
IPEX	Intelligent Payload Experiment
IR	Infrared

Abbreviations and Acronyms	Definition
IRIS	Interface Region Imaging Spectrograph
ISERV	ISS SERVIR Environmental Research and Visualization System
ISON	International Scientific Optical Network
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
IXO	International X-ray Observation
JASD	Joint Agency Satellite Division
JASON	Joint Altimetry Satellite Oceanography Network
JAXA	Japanese Space Agency (Japan Aerospace Exploration Agency)
JPSS	Joint Polar Satellite System
JUICE	Jupiter Icy Moons Explorer (ESA)
JWST	James Webb Space Telescope
KDP	Key Decision Point
L1	Lagrange point 1
LADEE	Lunar Atmosphere and Dust Environment Explorer
LCAS	Low-Cost Access to Space
LCC	life cycle cost
LDCM	Landsat Data Continuity Mission
LEO	Low Earth Orbit
LIS	Lightning Imaging Sensor
LISA	Laser Interferometer Space Antenna
LIST	Lidar Surface Topography
LLCD	Lunar Laser Communications Demonstration
LMSSC	Lockheed Martin Space Systems Company
LRD	Launch Readiness Date
LRO	Lunar Reconnaissance Orbiter
LWS	Living With a Star
MatISSE	Maturation of Instruments for Solar System Exploration
MAVEN	Mars Atmosphere and Volatile Evolution
MAX-C	Mars Astrobiology Explorer-Cacher
MEP	Mars Exploration Program
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
MetOp	Meteorological Operational
MMS	Magnetospheric Multiscale
MOMA	Mars Organic Molecule Analyzer
MOMA-MS	Mars Organic Molecule Analyzer Mass Spectrometer
MRO	Mars Reconnaissance Orbiter

Abbreviations and Acronyms	Definition
MSL	Mars Science Laboratory
N/A	Not applicable
NAC	NASA Advisory Council
NAI	NASA Astrobiology Institute
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NEOWISE	Near-Earth Object Wide-field Infrared Survey Explorer
NESSF	NASA Earth and Space Science Fellowship
NET	No earlier than
NEX	NASA Earth Exchange
NIAC	NASA Innovative Advanced Concepts
NI-SAR	NASA-India Space Research Organization Synthetic Aperture Radar
NLT	No later than
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	National Polar-Orbiting Partnership
NRA	NASA Research Announcement
NRC	National Research Council
NRO	National Reconnaissance Office
NSF	National Science Foundation
NSTC	National Science and Technology Council
NuSTAR	Nuclear Spectroscopic Telescope Array
OCE	Office of the Chief Engineer
OCO	Orbiting Carbon Observatory
OCT	Office of the Chief Technologist
OMPS	Ozone Mapper and Profiler Suite
ORS-3	Operationally Responsive Space-3
OSC	Orbital Sciences Corporation
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security Regolith Explorer
OSTM	Ocean Surface Topography Mission
PACE	Pre-Aerosol, Clouds, and Ecosystems
PATH	Precipitation and All-weather Temperature and Humidity
PDS	Planetary Data System
PI	Principal Investigator
PICASSO	Planetary Instrument Concepts for the Advance- ments of Solar System Observations
POES	Polar-orbiting Operational Environmental Satellites
R&A	Research and analysis

Abbreviations and Acronyms	Definition
RapidScat	Rapid Scatterometer
RBI	Radiation Budget Investment
RBSP	Radiation Belt Storm Probes
REDDI	Research, Development, Demonstration, and Infusion
RHESSI	Reuven Ramaty High Energy Solar Spectroscope Imager
ROSES	Research Opportunities in the Space and Earth Sciences
RPP	Reimbursable Projects Program
RPS	Radioisotope Power System
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar
SARA	Service and Advice for Research and Analyses
SAT	Strategic Astrophysics Technology
SBIR	Small Business Innovative Research
SCLP	Snow and Cold Land Processes
SDO	Solar Dynamics Observatory
SDT	Science Definition Team
SEM	Space Environment Monitor
SEPOF	Science Education and Public Outreach Forum
SET	Space Environment Testbed
SEXTANT	Station Explorer for X-ray Timing and Navigation
SI	International System of Units
SLS	Space Launch System
SMAP	Soil Moisture Active/Passive
SMD	Science Mission Directorate (NASA)
SOC	Solar Orbiter Collaboration
SOFIA	Stratospheric Observatory For Infrared Astronomy
SOHO	Solar and Heliospheric Observatory
SORCE	Solar Radiation and Climate Experiment
SpaceX	Space Explorations Technology Corporation
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SPP	Solar Probe Plus
SSERVI	Solar System Exploration Research Virtual Institute
STEM	Science, Technology, Engineering and Mathematics
STEREO	Solar Terrestrial Relations Observatory
STMD	Space Technology Mission Directorate (NASA)
STP	Solar Terrestrial Probes
STRG	Space Technology Research Grants

APPENDICES

Abbreviations and Acronyms	Definition
STTR	Small Business Technology Transfer
Suomi NPP	Suomi-National Polar-orbiting Partnership
SWOT	Surface Water and Ocean Topography
SXSW	South by Southwest
TBD	To be determined
TCTE	TSI (Total Solar Irradiance) Calibration Transfer Experiment
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TESS	Transiting Exoplanet Survey Satellite
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIMED	Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics
TIROS	Television Infrared Observation Satellite
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TSI	Total Solar Irradiance
TSIS	Total Solar Irradiance Sensor
TWINS	Two Wide-angle Imaging Neutral Atom Spectrometers
U.S.	United States
UHF	Ultra-High Frequency
ULA	United Launch Alliance
ULDB	Ultra Long Duration Balloon
UN	United Nations
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
USAF	United States Air Force
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USGCRP	United States Global Change Research Program
USGS	United States Geological survey
UV	ultraviolet
VIIRS	Visible Infrared Imager Radiometer Suite
WFIRST	Wide-Field Infrared survey Telescope
WISE	Wide-field Infrared survey Explorer
XMM	X-ray Multi-Mirror Mission

National Aeronautics and Space Administration

NASA Headquarters
Washington, DC 20546

www.nasa.gov